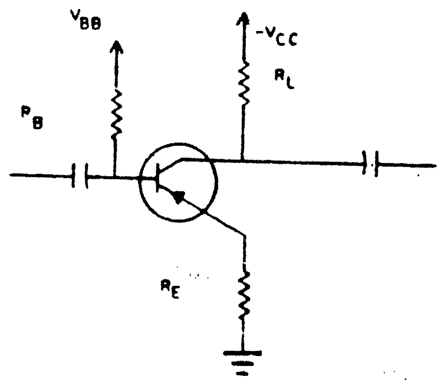
STUDENT'S GUIDE

FOR

ADVANCED FIRST-TERM AVIONICS COURSE

CLASS A1

C-100-2010



UNIT II

CNTT-M1704

PREPARED BY

NAVAL AIR TECHNICAL TRAINING CENTER

NAVAL AIR STATION MEMPHIS

MILLINGTON TENNESSEE

PREPARED FOR

CHIEF OF NAVAL TECHNICAL TRAINING

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FOREWORD

The purpose of this _Student's Guide_ is to assist you in completing the "Transistor Theory," Unit II, of the Advanced First-Term Avionics Course. The proper use of this guide will increase your abilities in the above mentioned areas, while building a basis upon which your future training will be built.

The table of contents lists the page numbers for safety notices, notetaking sheets, information sheets, and references that will further enhance your abilities and skills as an aviation electronics technician.

SAFETY NOTICE

As a Navy electronics technician, you will be required to perfo safe and efficient maintenance on various types of electronic equipment. Not only your life, but the lives of many others wi depend on your being safety conscious at all times. It is the responsibility of all Navy and Marine Corps personnel to preven accidents. This can be done if everyone develops conscientious safety habits and observes all precautions when performing main nance of any type. Always remember:

SAFETY CANNOT BE OVERSTRESSED!!!!!

HOW TO USE THIS STUDENT'S GUIDE

This "Student's Guide" has been prepared for you to use while you are attending the Advanced First-Term Avionics Course (Class A1). Ample space has been provided for taking notes on the required lesson information. Remember when you are in class, the information being provided by your instructor is information you will need in performing your Navy job.

This volume contains the following:

1. Notetaking sheets, containing lesson topic outlines, illustrations, and ample space for personal notetaking.

2. Information sheets to provide information pertinent to your training.

GOOD LUCK! Learn all you can!

UNIT II CLASS SCHEDULE

Unit II is two weeks long and starts the afternoon of the fifth day of the second week. The periods run from 77 to 156, with the last period ending halfway through the fifth day of the fourth week.

The schedule is as follows:

TOPIC NO.	TYPE	PERIOD	TOPIC
SECOND WEEK			
Fifth Day			
2.1	Class	67	Series Resonance
		78	
		79	
2.2	Class	80	Parallel Resonance
THIRD WEEK			
First Day			
2.2	Class	81	Parallel Resonance
2.3	Class	82	Physics Overview
		83	
		84	
2.4	Class	85	Semiconductor Physics
		86	
		87	
		88	
Second Day			
2.4	Class	89	Semiconductor Physics
2.5	Lab	90	PN Junctions (Laboratory)
		91	
2.6	Class	92	Junction Transistors
		93	
		94	
		95	
		96	

TOPIC NO.	TYPE	PERIOD	TOPIC
Third Day			
2.7	Lab	97	Junction Transistors (Laboratory)
		98	
		99	
		100	
2.8	Class	101	Biasing Arrangements
		103	
		104	
Fourth Day			
2.8	Class	105	Biasing Arrangements
		106	
		107	
2.9	Lab	108	Biasing Arrangements (Laboratory)
		109	
		110	
		111	
		112	
Fifth Day			
	Class	113	Unit/Module Test: Criterion Test/ Written Examination
		114	
		115	
2.10	Class	116	Decibels
		117	
2.11	Class	118	Feedback Amplifiers
		119	
		120	
FOURTH WEEK			
First Day			
2.11	Class	121	Feedback Ampilfiers
		122	
		123	
2.12	Class	124	Direct Coupled and Operational Amplifiers
		125	
		126	
		127	
		128	

TOPIC NO.	TYPE	PERIOD	TOPIC
Second Day			
2.13	Class	129	Transformer Coupled Ampilfiers
		130	
		131	
		132	
2.14	Class	133	Special Devices
		134	
		135	
		136	
Third Day			
2.14	Class	137	Special Devices
		138	
		139	
		140	
2.15	Class	141	Vacuum-Tube Fundamentals
		142	
2.16	Class	143	Triodes
		144	
Fourth Day			
2.16	Class	145	Triodes
		146	
		147	
		148	
2.17	Class	149	Multielement Tubes
		150	
		151	
		152	
Fifth Day			
	Class	153	Unit/Module Test: Criterion Test/Written Examination
		154	
		155	
		156	

UNIT II HOMEWORK SCHEDULE

Homework is MANDATORY! In Unit II, homework is assigned with each individual lesson topic. Homework is due on morning following the day when the lesson was completed. Each assignment sheet will be checked by an instructor for correctness and completion. Information sheets assigned with lesson topics are considered as homework. Failure to complete assigned homework may result in disciplinary action.

Assignment Sheet	Period Due
2.1.1A	81
2.2.1A	89
2.3.1A	89
2.4.1A	97
2.6.1A	97
2.8.1A	113
2.10.1A	121
2.11.1A	129
2.12.1A	129
2.13.1A	137
2.14.1A	145
2.15.1A	145
2.16.1A	153
2.17.1A	153

UNIT LEARNING OBJECTIVES

TERMINAL OBJECTIVE

1.0 SOLVE problems related to electronic circuits, using basic mathematics, algebra, and trigonometry. A formula sheet, trigonometric tables, and a Universal Time Constant Chart will be provided. Performance must be in accordance with Mathematical principles outlined in Mathematics, Vol. I, NAVPERS 10069 (series), Mathematics, Vol. III, NAVPERS 10073 (series), Basic Electronics, Vol. I, NAVPERS 10087 (series), and Basic Electricity, NAVPERS 10086 (series). Performance will be measured by a written multiple-choice examination.

2.0 ANALYZE the internal structure and operation of semiconductor junctions by tracing majority and minority current flow through a given semiconductor device, in accordance with quantum mechanical principles outlined in Basic Electronics, Vol. I, NAVPERS 10087 (series) and Aviation Electronics 3 & 2, NAVEDTRA 10317 (series). Performance will be measured by a written multiple-choice examintion.

3.0 Mathematically ANALYZE the operation of given basic semiconductor circuits by solving problems in terms of voltage, current, reactance, and frequency. A formula sheet will be provided. Responses must be in accordance with Basic Electronics, Vol. I, NAVPERS 10087 (series), and performance will be measured by a written multiple-choice examination.

4.0 ANALYZE the internal structure and operation of vacuum-tube circuits by identifying elements and their functions and by SOLVING problems in terms of voltage, current, resistance and biasing. Responses must be in accordance with information outlined in Basic Electronics, Vol. I, NAVPERS 10087 (series). Performance will be measured by a written multiple choice examination. A formula sheet will be provided.

ENABLING OBJECTIVES

1.1 SOLVE problems involving addition, subtraction, multiplication, and division of radicals and exponents, using the laws of exponents. Response must be in accordance with Mathematics, Vol. I, NAVPERS 10069 (series). Performance will be measured by a written multiple-choice examination.

1.2 SOLVE problems involving the addition, subtraction, multiplication, division, evaluation, and simplification of algebraic expressions. Response must be in accordance with Mathematics, Vol. I, NAVPERS 10069 (series). Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

1.3 SOLVE for the variables in simultaneous linear equations, using the principles of matrix algebra. Responses must be in accordance with <u>Mathematics</u>, Vol. III, NAVPERS 10073 (series). Performance will be mesured by a written multiple-choice examination. A formula sheet will be provided.

1.4 SOLVE for total capacitance, RC time, curent, and voltage values of a simple RC switching circuit. Response must be in accordance with <u>Basic Electricity</u>, NAVPERS 10086 (series). Performance will be measured by a written multiple-choice examination. A formula sheet and a Universal Time Constant Chart will be provided.

1.5 SOLVE for total inductance, L/R time, current, and voltage values of a simple L/R switching circuit. Response must be in accordance with <u>Basic Electricity</u>, NAVPES 10086 (series). Performance will be measured by a written multiple-choice examination. A formula sheet and a Universal Time Constant Chart will be provided.

1.6 SOLVE for unknown current, voltage, and resistance values of electronic circuits containing source characteristics and voltage dividers. Response must be in accordance with <u>Basic Electricity</u>, NAVPERS 10086 (series). Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

1.7 SOLVE for unknown values of current, voltage, reactance, and power in series and parallel a-c circuits. Response must be in accordance with <u>Basic Electricity</u>, NAVPES 10086 (series). Performance will be measured by a written multiple-choice examination. A formula sheet and trigonometric tables will be provided.

1.8 SOLVE for unknown values of current, voltage, reactance, frequency, bandwidth, and circuit "Q", in series and parallel resonant circuits. Response will be in accordance with <u>Basic Electronics</u>, Vol. I, NAVPERS 10087 (series). Performance will be measured by a written multiple-choice examination. A formula sheet and trigonometric tables will be provided.

2.1 SELECT, from a given list, correct statements concerning the structure of an atom, given an element from the Periodic Table of Chemical Elements. Responses must be in accordance with <u>Basic Electronics</u>, Vol. I, NAVPERS 10087 (series). Performance will be measured by a written multiple-choice examination.

2.2 SELECT, from given lists, correct statements related to the properties of heat, sound, cryogenics, and the electromagnetic spectrum. Responses must be in accordance with <u>Aviation Electronics Technician 3 & 2</u>, NAVEDTRA 10317 (series). Performance will be measured by a written multiple-choice examination.

2.3 DETERMINE normal biasing polarities of semiconductor junctions by ANALYZING majority and minority current through a given semiconductor circuit. Responses must be in accordance with quantum principles outlined in Basic Electronics, Vol. I, NAVPERS 10087 (series). Performance will be measured by a written multiple-choice examination.

3.1 DETERMINE biasing arrangements of semiconductor circuits by SOLVING problems in terms of voltage, current, reactance, and frequency. Responses must be in accordance with Basic Electronics, Vol. I, NAVPERS 10087 (series). Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

3.2 DETERMINE capabilities, electrical characteristics, advantages, and disadvantages of given semiconductor circuits by SOLVING problems in terms of voltage, current, reactance, and frequency. Responses must be in accordance with Basic Electronics, Vol. I, NAVPERS 10087 (series). A formula sheet will be provided.

3.3 COMPUTE decimal gain and loss in terms of the voltage and power of a given semiconductor amplifier circuit. Responses must be in accordance with Basic Electronics, Vol. I, NAVPERS 10087 (series). A formula sheet will be provided. Performance will be measured by a multiple-choice examination.

3.4 BUILD basic semiconductor amplifier circuits (under supervision). MEASURE values and RECORD measurements, calculations, and evaluations on a job sheet, given necessary test equipment and an RCA 6F16 transistor trainer. Accuracy will be measured in accordance with information contained in Basic Electronics, Vol. I, NAVPERS 10087 (series).

4.1 SELECT, from given lists, the names and functions of the elements contained within a vacuum-tube. Responses must be in accordance with information outlined in Basic Electronics, Vol. I, NAVPERS 10087 (series). Performance will be measured by a written multiple-choice examination.

4.2 SOLVE problems in terms of voltage, current, resistance and biasing, using vacuum-tube formulas and tube constants. Responses must be in accordance with information outlined in Basic Electronics, Vol. I, NAVPERS 10087 (series). Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

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NOTETAKING SHEET 2.1.1N

SERIES RESONANCE

REFERENCE: Basic Electronics, Vol. I, NAVPERS 10087-C, Chapter 10, pages 188 to 202.

NOTETAKING OUTLINE:

I. General Information

II. Resonant Frequency

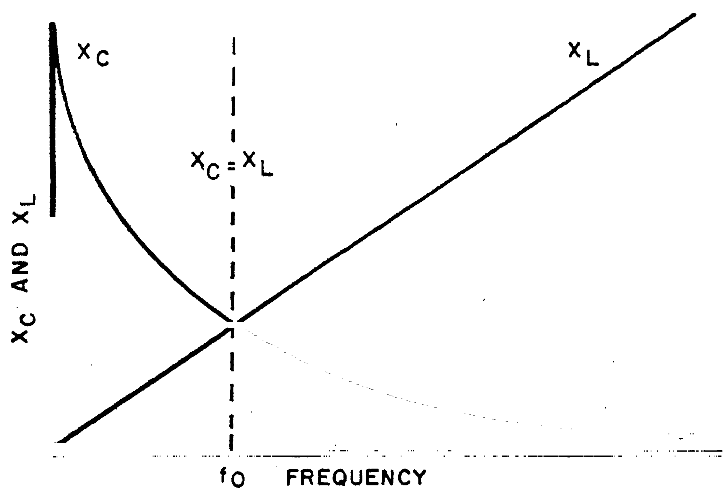


Figure 1. Reactance Curves for Series RLC Circuit

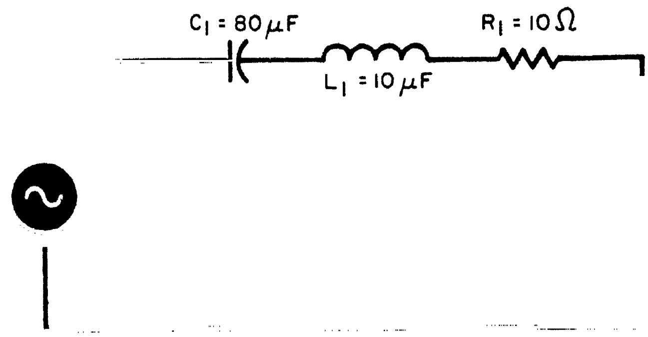


Figure 2. Series Resonant Circuit

III. Resonant Series Circuit Analysis

IV. Circuit Q

V. Series RLC Circuit Analysis

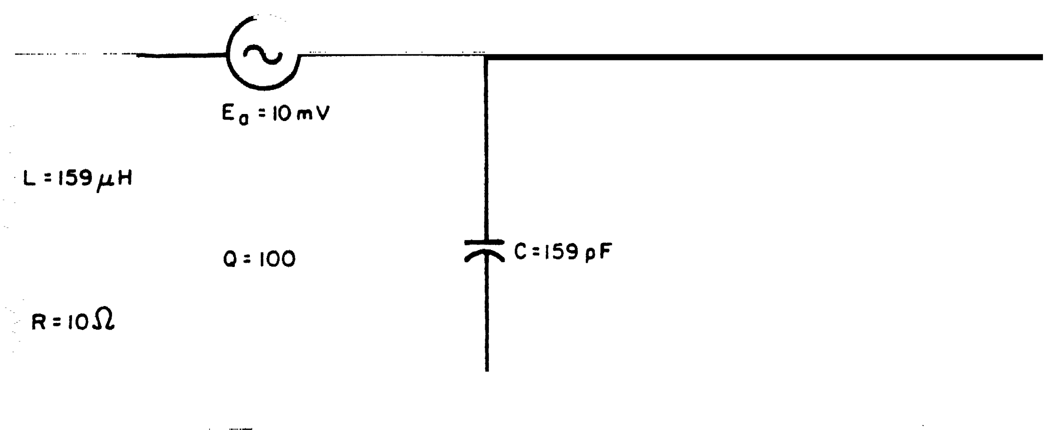


Figure 3. Series RLC circuit

VI. Bandwidth Considerations

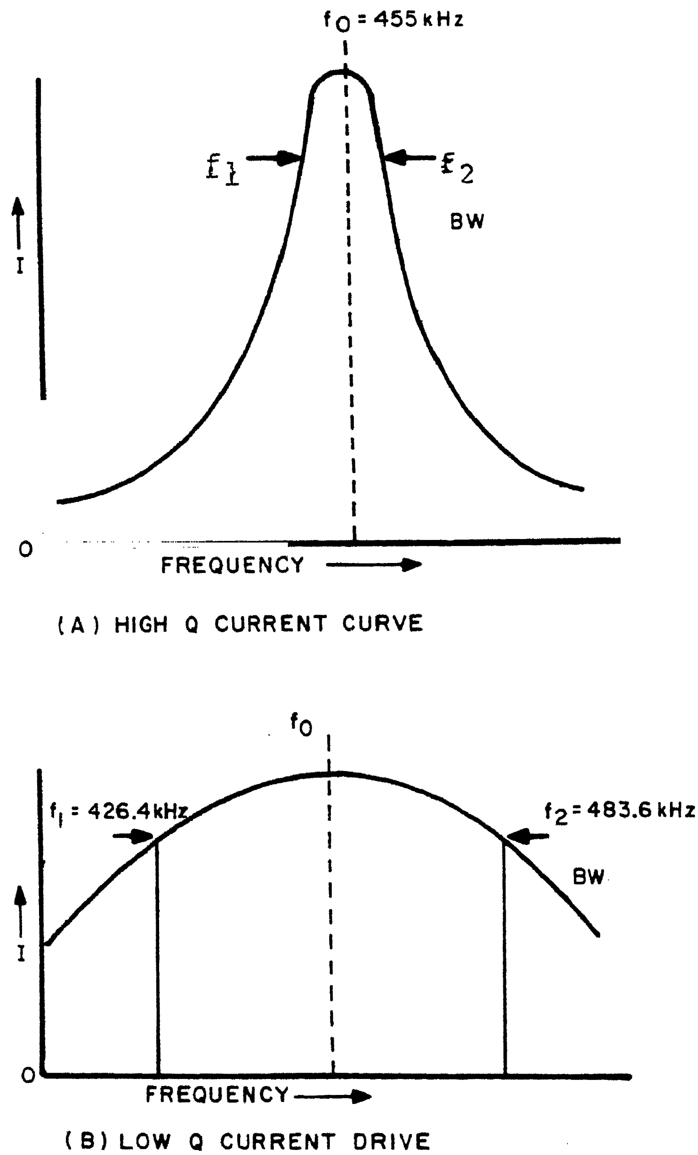


Figure 4. Bandwidth curves

VII. Applications of Series Resonant Circuits.

NOTETAKING SHEET 2.2.1N

PARALLEL RESONANCE

REFERENCES:

1. Basic Electronics, Vol. 1, NAVPERS 10087-C, Chapter 10, pages 203 to 209.

2. Robert L. Shrader, Electronic Communication, Fourth Edition, McGraw-Hill, Inc., 1980, Chapter 8, pages 123-131.

NOTETAKING OUTLINE:

I. Ideal Parallel Resonance

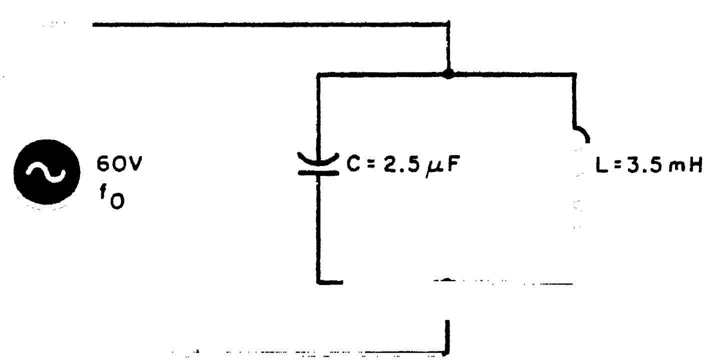


Figure 1. Parallel LC Circuit at Resonance

II. Practical Parallel Rsonance

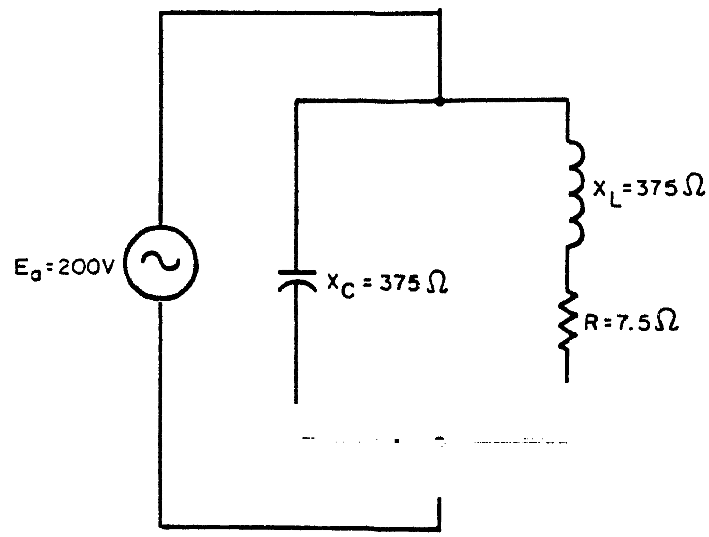


Figure 2. Parallel Resonant Circuit with Parallel Resistance.

III. Bandwidth Considerations

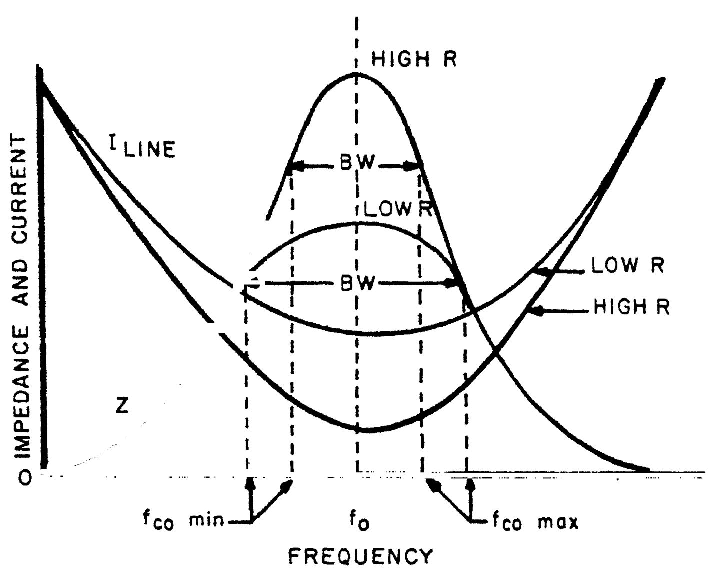


Figure 3. Effect of Shunt Resistance on BW, I_{line}, and Z.

IV. Applications for Parallel Resonant Circuits

NOTETAKING SHEET 2.3.1N

PHYSICS OVERVIEW

REFERENCE:

Williams, Metcalf, Trinklein, and Lefler. _Modern Physics_. New York: Holt, Rinehart, and Winston, 1968. Chapters 1, 7, 14-18, and 27.

NOTETAKING OUTLINE

I. Matter

II. Energy

III. The Relationship Between Matter and Energy

IV. Cryogenics

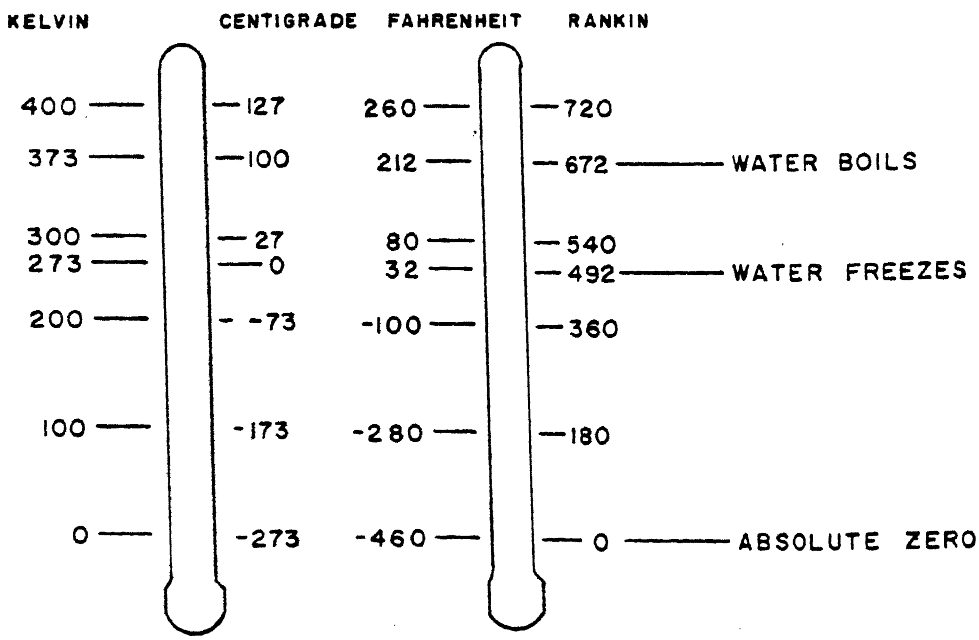


Figure 1. Temperature Scales

ELEMENT	TEMPERATURE AT WHICH ELEMENT BECOMES SUPERCONDUCTIVE
Niobium	8.0 K.
Lead	7.2 K.
Tantalum	4.4 K.
Mercury	4.2
Thorium	1.4
Aluminum	1.2
Zinc	0.91
Titanium	0.4

Figure 2. Superconductivity Chart

V. Sound

VELOCITY OF SOUND	MEDIUM
1,087 FT./SEC	IN AIR AT 32° F
4,794 FT./SEC	IN WATER
16,500 FT./SEC	IN STEEL

Figure 3. Velocity of Sound in Various Mediums

VI. Light

VII. Heat

A. Sources of heat

B. Units of heat measurement

C. Methods of heat transference

INFORMATION SHEET 2.4.1I

SEMICONDUCTOR PHYSICS

INTRODUCTION

An understanding of basic physical and chemical properties is essential to the study of electronics. Even the more complex electronic devices can be reduced to a study of electron behavior in solids or gases. To follow explanations for semiconductor devices, for example, the technician must have a knowledge of how atoms bond together to make a crystal.

REFERENCE: Dull, Metcalf, and Williams. Modern Physics. New York, N.Y.: Holt, Rinehart, and Winston, Inc., 1963. Chapter 6, pages 133-151.

INFORMATION

I. INTRODUCTION TO THE PERIODIC CHART OF THE ATOMS

A. Many of the early scientists saw that the periodicity or rhythm to atomic behavior could be shown graphically. Today, the physical significance of such a rhythm is known. The "Periodic Chart of the Atoms" is the graphic portrayal of this significance. As late as 1870, there were only 63 elements known. At this time, some system of cataloging the atoms was attempted. First, they cataloged by atomic weights. The weights of the elements were soon found to be variable, depending on the number of isotopes. A little later, it was found that the atomic number (number of protons in the nucleus) was more stable. Even though the number of elements known did not complete the chart, it gave rise to speculation that the missing atomic numbers may be unknown elements. By 1900, the inert gases were discovered and the chart began to fill out. In 1913, the isotopes were discovered. They also fit into the rhythm of the chart. An isotope is a basic element with a different atomic weight. It was simply a matter of listing all isotopes of an element under the same position on the Periodic Chart; they all have the same atomic number but different atomic weights. Today, we have the Periodic Chart in its entirety from Atomic Number 1 to Atomic Number 103. Refer to figure 1, Periodic Chart; there are no gaps between the known first and last elements, but this does not mean to say that there are no more beyond 103. Even the men who built our modern chart left space for three more elements. They even labeled these blocks; 104, 105, and 106.

B. The present chart sets forth graphically or numerically some thirty odd facts concerning each atom or element. Each atom is placed on the periodic chart according to its number of shells and outer planets (electrons). On the "Periodic Chart," figure 1, the column number is the number of outermost planets or valence electrons; its row number is the number of shells. The Periodic System is now complete with all stable atoms discovered and assigned numbers and position. The outer planet system was completed by the discovery of the six inert gases of the atmosphere, Group VIII atoms. Each row (or double row) ends with one of these inert atoms.

II. PERIODIC CHART DATA

A. Atomic symbol

1. All atoms have symbols. The "Periodic Chart" shows the atomic symbols; examples are hydrogen, H; lead, P_b; oxygen, O; and uranium, U.

2. All elements exist in one of three physical forms. The forms are solids, liquids, or gases. The chart lists each element's symbol by a color that represents the form in which it is found to exist in nature. (Colors not shown in figure 1).

3. Black symbols represent solids. Some examples of solids are carbon, silicon, iron, and gold.

4. Blue symbols represent liquids. There ae only four known liquids; bromine, mercury, gallium, and cesium.

5. Orange symbols represent gases. Some examples are hydrogen, oxygen, argon, krypton, and zenon.

B. Atomic number

1. The atomic number appears on the chart as the large black number. Refer to figure 1, "Periodic Chart."

2. The atomic number represents the number of protons in the nucleus of the atom. Since atoms are electrically neutral, they must contain equal numbers of protons and electrons. Thus, the atomic number also equals the number of electrons in an atom. The atomic number is the "key" to the periodic chart. Refer to Table I, "Distribution of Electrons"; starting with hydrogen, which has one proton and one electron, each successive element increases by one proton and one electron. This increase by one takes place throughout the chart. The last known element is lawrencium, and it has 103 protons in the nucleus.

3. The symbol for the atomic number is Z.

   4. Examples of the correct notation to indicate the elements' atomic number and atomic symbol is shown below:

      a. $_1H$--Hydrogen, Z = 1

      b. $_2He$--Helium, Z = 2

      c. $_{26}Fe$--Iron, Z = 26

      d. $_{54}Xe$--Xenon, Z = 54

C. Isotopes

   1. When a proton is added to the nucleus and an electron is added to the shells, a new atom is formed. If a neutron enters the nucleus a new atom is not formed. Although dead weight is added, such an atom behaves chemically as before. These atoms with the same number of protons but different numbers of neutrons ae called <u>isotopes</u> of the same element.

   2. An example of an element with three isotopes in hydrogen (H). Shown in figure 2 are the three isotopes of hydrogen.

   3. The basic hydrogen atom, protium, has one proton and no neutrons.

GROUPS

	I	II	III	IV	V	VI	VII	VIII			
1	1 H Hydrogen 1.00797							2 He Helium 4.0026	VALENCE GROUPS		
2	3 Li Lithium 6.939	4 Be Beryllium 9.0122	5 B Boron 10.811	6 C Carbon 12.01115	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984	10 Ne Neon 20.183	CHART OF ATOMS		
3	11 Na Sodium 22.9898	12 Mg Magnesium 24.312	13 Al Aluminum 26.9815	14 Si Silicon 28.086	15 P Phosphorus 30.973	16 S Sulfur 32.064	17 Cl Chlorine 35.453	18 Ar Argon 39.948			
4	19 K Potassium 39.102	20 Ca Calcium 40.08	21 Sc Scandium 44.956	22 Ti Titanium 47.90	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.9380	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.71	
	29 Cu Copper 63.54	30 Zn Zinc 65.37	31 Ga Gallium 69.72	32 Ge Germanium 72.59	33 As Arsenic 74.9216	34 Se Selenium 78.96	35 Br Bromine 79.909	36 Kr Krypton 83.80			
5	37 Rb Rubidium 85.47	38 Sr Strontium 87.62	39 Y Yttrium 88.905	40 Zr Zirconium 91.22	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium (99)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.905	46 Pd Palladium 106.4	
	47 Ag Silver 107.870	48 Cd Cadmium 112.40	49 In Indium 114.82	50 Sn Tin 118.69	51 Sb Antimony 121.75	52 Te Tellurium 127.60	53 I Iodine 126.9044	54 Xe Xenon 131.30			
6	55 Cs Cesium 132.905	56 Ba Barium 137.34	57 La Lanthanum 138.91	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Wolfram Tungsten 183.85	75 Re Rhenium 186.2	76 Os Osmium 190.2	77 Ir Iridium 192.2	78 Pt Platinum 195.09	
	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.37	82 Pb Lead 207.19	83 Bi Bismuth 208.980	84 Po Polonium (210)	85 At Astatine (210)	86 Rn Radon 222.	Figure 1		
7	87 Fr Francium (223)	88 Ra Radium (226)	89 Ac Actinium (227)	104	105	106					

6	58 Ce 140.12	59 Pr 140.907	60 Nd 144.24	61 Pm (145)	62 Sm 150.35	63 Eu 151.96	64 Gd 157.25	65 Tb 158.924	66 Dy 162.50	67 Ho 164.930	68 Er 167.26	69 Tm 168.934	70 Yb 173.04	71 Lu 174.97
7	90 Th 232.038	91 Pa (231)	92 U 238.03	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (249)	98 Cf (251)	99 Es (254)	100 Fm (253)	101 Md (256)	102 No (254)	103 Lw (257)

Figure 1

Table I

Distribution of Electrons

ATOMIC NO.	ELEMENT	SHELLS K	L	M	N	O
1	Hydrogen	1				
2	Helium	2				
3	Lithium	2	1			
4	Beryllium	2	2			
5	Boron	2	3			
6	Carbon	2	4			
7	Nitrogen	2	5			
8	Oxygen	2	6			
9	Fluorine	2	7			
10	Neon	2	8			
11	Sodium	2	8	1		
12	Magnesium	2	8	2		
13	Aluminum	2	8	3		
14	Silicon	2	8	4		
15	Phosphorus	2	8	5		
16	Sulphur	2	8	6		
17	Chlorine	2	8	7		
18	Argon	2	8	8		
19	Potassium	2	[illegible]	8	1	
20	Calcium	2	8	8	2	
21	Scandium	2	8	9	2	
22	Titanium	2	8	10	2	
23	Vanadium	2	8	11	2	
24	Chromium	2	8	12	2	
25	Manganese	2	8	13	2	
26	Iron	2	8	14	2	
27	Cobalt	2	8	15	2	
28	Nickel	2	8	16	2	
29	Copper	2	8	18	1	
30	Zinc	2	8	18	2	
31	Gallium	2	8	18	3	
32	Germanium	2	8	18	4	
33	Arsenic	2	8	18	5	
34	Selenium	2	8	18	6	
35	Bromine	2	8	18	7	
36	Krypton	2	8	18	8	
37	Rubidium	2	8	18	8	1
38	Strontium	2	8	18	8	2
39	Yttrium	2	8	18	9	2
40	Zirconium	2	8	18	10	2
41	Niobium	2	8	18	11	2
42	Molybdenum	2	8	18	12	2

ATOMIC NO.	ELEMENT	SHELLS K	L	M	N	O	P
43	Technitium	2	8	18	13	2	
44	Ruthenium	2	8	18	14	2	
45	Rhodium	2	8	18	15	2	
46	Palladium	2	8	18	16	2	
47	Silver	2	8	18	18	1	
48	Cadmium	2	8	18	18	2	
49	Indium	2	8	18	18	3	
50	Tin	2	8	18	18	4	
51	Antimony	2	8	18	18	5	
52	Tellurium	2	8	18	18	6	
53	Iodine	2	8	18	18	7	
54	Xenon	2	8	18	18	8	
55	Cesium	2	[illegible]	18	[illegible]	8	1
56	Barium	2	8	18	18	8	2
57	Lanthanum	2	8	18	18	9	2
58	Cerium	2	8	18	19	9	2
59	Pra'mium	2	8	18	20	9	2
60	Neodmium	2	8	18	21	9	2
61	Promethium	2	8	18	22	9	2
62	Samarium	2	8	18	23	9	2
63	Europium	2	8	18	24	9	2
64	Gadolinium	2	8	18	25	9	2
65	Terbium	2	8	18	26	9	2
66	Dysprosium	2	8	18	27	9	2
67	Holmium	2	8	18	28	9	2
68	Erbium	2	8	18	29	9	2
69	Thulium	2	8	18	30	9	2
70	Ytterbium	2	8	18	31	9	2
71	Lutetium	2	8	18	32	9	2
72	Hafnium	2	8	18	32	10	2
73	Tantalum	2	8	18	32	11	2
74	Tungsten	2	8	18	32	12	2
75	Rhenium	2	8	18	32	13	2
76	Osmium	2	8	18	32	14	2
77	Iridium	2	8	18	32	15	2
78	Platinum	2	8	18	32	16	2
79	Gold	2	8	18	32	18	1
80	Mercury	2	8	18	32	18	2
81	Thallium	2	8	18	32	18	3
82	Lead	2	8	18	32	18	4
83	Bismuth	2	8	18	32	18	5
84	Polonium	2	8	18	32	18	6

Table I (Cont'd)

ATOMIC NO.	ELEMENT	K	L	M	N	O	P	Q
85	Astatine	2	8	18	32	18	7	
86	Radon	2	8	18	32	18	8	
87	Francium	2	8	18	32	18	8	1
88	Radium	2	8	18	32	18	8	2
89	Actinium	2	8	18	32	18	9	2
90	Thorium	2	8	18	32	19	9	2
91	Protactinium	2	8	18	32	20	9	2
92	Uranium	2	8	18	32	21	9	2
93	Neptunium	2	8	18	32	22	9	2
94	Plutoium	2	8	18	32	23	9	2
95	Americium	2	8	18	32	24	9	2
96	Curium	2	8	18	32	25	9	2
97	Berkelium	2	8	18	32	26	9	2
98	Californium	2	8	18	32	27	9	2
99	Einsteinium	2	8	18	32	28	9	2
100	Fermium	2	8	18	32	29	9	2
101	Mendelevium	2	8	18	32	30	9	2
102	Nobelium	2	8	18	32	31	9	2
103	Lawrencium	(Unknown)						

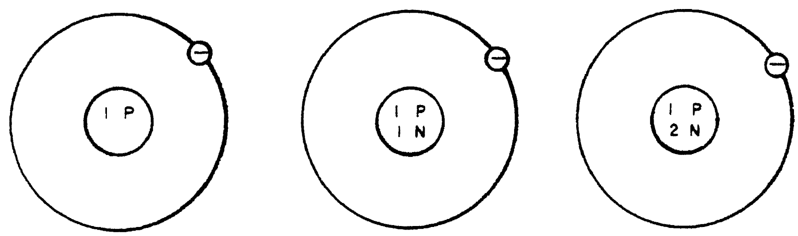


Figure 2

The second hydrogen atom, deuterium, has 1 proton and 1 neutron. The third hydrogen atom, tritium, has 1 proton and 2 neutrons. The three hydrogen isotopes ($^{1}_{1}H$, $^{2}_{1}H$, and $^{3}_{1}H$) given individual names to identify them. These names ae protium ($^{1}_{1}H$), deuterium ($^{2}_{1}H$), and tritium ($^{3}_{1}H$). Almost all elements have more than one isotope.

D. Atomic Weight

1. The atomic weight is the weighted <u>average</u> of the isotopes based on their relative abundance. The atomic weight is shown in figure 1, "Periodic Chart."

2. The average weight of the three isotopes in hydrogen is 1.00797 AMU (Atomic Mass Units) (1 AMU = 1.66×10^{-24} grams). The figure for atomic weight is a relative number and its only real importance is to the chemist.

3. The atomic weight is not the same as the number of protons and neutrons in the nucleus. The mass number is the number of protons and neutrons and is a whole number.

E. Electron Shells

1. The orbits in which electrons must revolve about the nucleus of an atom are called electron shells, or quanta levels. The shells are labelled K, L, M, N, O, P, Q from the innermost (K) to the outermost (Q). Table I, "Distribution of Electrons," shows the shells and the number of electrons existing in each one.

2. The shells begin filling with electrons from the innermost shell (K) and work outward. In most cases, the "K" shell fills first, then the "L" shell, and so on. This is not an absolute law; there are some irregularities. At this time we are not interested in the reason for the irregularities.

3. Study Table 1, "Distribution of Electrons", and notice that none of the elements has more than two electrons in the first shell (K). In the case of hydrogen, there is only one electron and it is in the "K" shell. In all other elements, only two electrons can exist in the "K" shell. To predict the maximum number of electrons that may occupy any given shell, use the equation $2(N^2)$ (N indicates the number of the shells). In the case of the first shell (K), the equation states:

$$2(N^2)$$

$$2(1^2)$$

$$2(1) = 2 \text{ electrons.}$$

The "K" shell in any element cannot contain more than two electrons. In the second shell (L), the equation states:

$$2(N^2)$$

$$2(2^2)$$

$$2(4) = 8 \text{ electrons.}$$

The "L" shell in any element cannot contain more than 8 electrons. All electrons do contain the maximum of 8 electrons except those that do not have enough electrons available to fill the shell (Z = 1 to Z = 9.) For example, Germanium; the equation states: "K" shell, 2 electrons; "L" shell, 8 electrons; "M" shell, 18 electrons; and "N" shell, 32 electrons. Refer to Table 1, "Distribution of Electrons." The table shows that germanium has 32 electrons (Atomic Number 32), and they are distributed "K" = 2, "L" = 8, "M" = 18, "N" = 4. The last shell in germanium (N) only contains 4 electrons, even though the equation predicts 32 electrons; this is because only 4 electrons are available, not 32. In no case will a shell contain more electrons than our equation predicted, but in many cases shells will contain less than predicted.

F. Subshells

1. The next question that should come to mind after studying Table 1 is, why do some elements have partially full shells and then the next shell out from this shell is also partially filled? An example of this is potassium, (Z = 19): notice the "K" shell = 2, "L" shell = 8, "M" shell = 8, "N" shell = 1. To explain why the "M" shell did not take the one electron that went to the "N" shell, we must delve deeper into the construction of the shells.

2. The K, L, M, N, O. P, Q shells are called the <u>main shells</u>. Each main shell after the "K" shell is made <u>up of subshells</u>. The number of subshells (or suborbitals) that are present within a main shell is shown in figure 3.

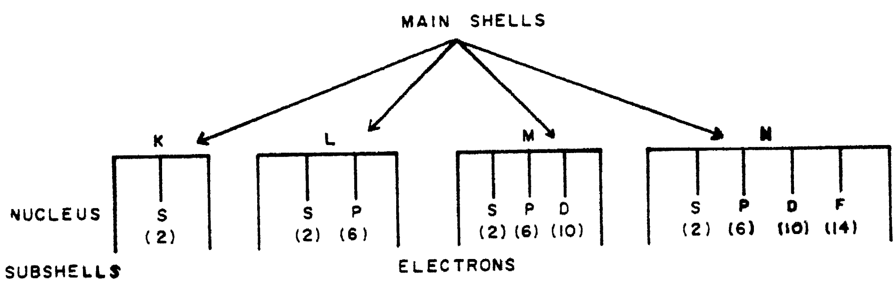


Figure 3

Note, in figure 3, each subshell that exists within a main shell as a set number of electrons. Each one of the "S" subshells in any main shell contains two electrons. Each succeeding subshell always has four electrons more than its preceding subshell. Remember, it was stated earlier that a main shell will fill, in most cases, before the next main shell begins. To be more specific, a subshell will fill prior to the next subshell out within a main shell. If a subshell in the "M" shell cannot be filled, the electrons will move out to the "S" subshell in the "N" main shell. An example of this is again potassium (Z = 19). Refer to figure 4.

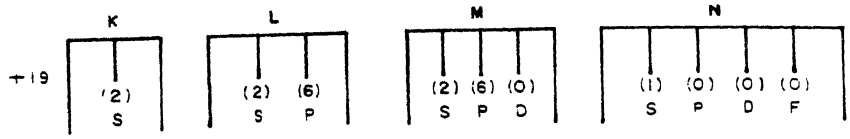


Figure 4

3. In the case of potassium, the "M" shell has the "P" subshell full. The last electron would not have completed the "D" subshell, so it was moved out to the next shell In most cases, this will happen; this is not, however, the law. A brief review of Table I, "Distribution of Electrons", will show that a number of elements deviate from the above. The majority do have some continuity a least through the "M" shell.

Group (or column)

1. Each group or column on the "Periodic Chart", figure 1, contains atoms of similar behavior in vertical alignment, since the Roman numeral number is equal, in general, to the number of valence electrons which fix the properties of the atoms. The Roman numeral at the head of each column indicates the column number and in general the number of such outer electrons.

2. The grouping of the elements according to valence electrons gives a ready reference to the electrical characteristics of the particular elements. Group I elements all have a valence of one electron. Note on the "Periodic Chart", figure 1, that copper is in Group I; copper is a good conductor. On the opposite end of the chart is Group VIII. Group VIII includes all the inert elements. Inert elements are those elements whose outermost shell (or subshell within a shell) is full. These elements in Group VIII will no

4. Groups V, VI, and VII are electrical insulators; they will readily accept an electron. These elements will accept electrons in an attempt to fill their outermost shell and become chemically stable.

5. Group VIII is the perfect electrical insulator. These are the "inert" elements". They will not give up or accept electrons. They contain a full outermost shell (or subshell within a shell). The breakdown of the "inert" elements can be seen by referring to Table 1, "Distribution of Electrons." Note that the "inert" elements are underlined.

6. Group IV is the "semiconductor" group. These elements have four electrons in their valence. They will either accept <u>or</u> give up electrons in an attempt to become chemically stable. For this reason, Group IV elements lie between conductors and insulators - semiconductor.

INFORMATION SHEET 2.4.2I

SEMICONDUCTOR PHYSICS

INTRODUCTION

Prior to the last twenty years, literature on solid state research was limited. The information accumulated regarding the copper oxide rectifier and germanium and silicon crystals led to the development of the transistor. A semiconductor, from which transistors are made, is an electronic conductor with resistivity in the range between that of a conductor and an insulator. The phenomenom of transistor action is unexplainable by electron theory alone, and a new theory is used which is called hole flow. It is essential that the technician have a basic understanding of solid-state physics in order to be able to understand the operation of a transistor.

REFERENCES:

1. Milton S. Kiver, Transistor and Integrated Electronics. New York, N.Y.: McGraw-Hill Book Company, 1972, Fourth Edition.

2, Slurzburg and Osterheld, Essentials of Radio--Electronics. New York, N.Y.: McGraw-Hill Book Company, 1961, Second Edition.

INFORMATION

I. Introduction

A. The story of the transistor is, in large measure, the story of matter and how the scientists at the Bell Telephone Laboratories have been able to make that matter amplify electric currents. If we consider the vacuum tube as man's first significant advance into the field of communication, then the transistor must certainly be heralded as man's second most important step.

B. The first public announcement of the transistor was made in June 1948. Thus, in terms of time, the transistor does to compare with vacuum tubes. In terms of application, however, it must be classed with the vacuum tube. And while there is probably no prospect that it will completely replace the vacuum tube, the transistor has nevertheless made serious inroads in a field that was once exclusively the province of the vacuum tube.

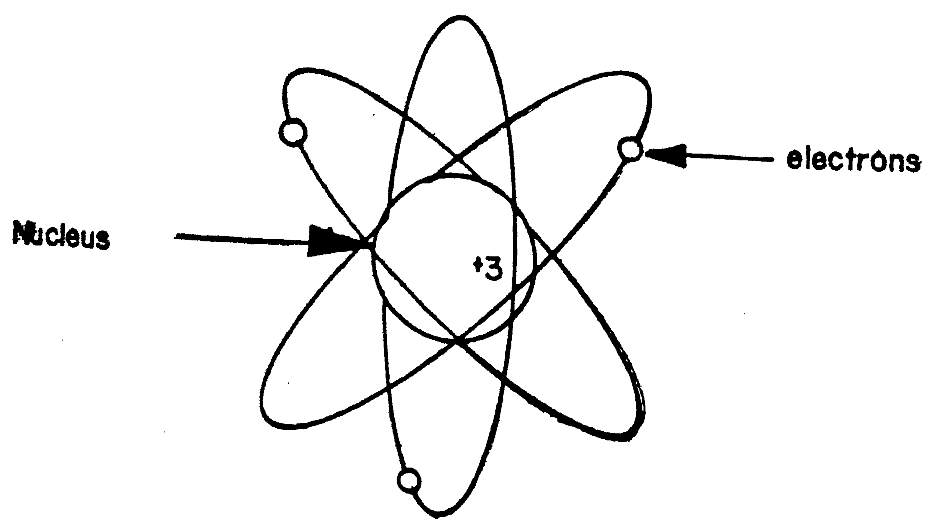
C. The most obvious attraction of transistors lies in their higher operating efficiency and smaller size than comparable electron tubes. A transistor, being a solid, required

no special envelope surrounding a vacuum; furthermore, it requires no filament heating element to serve as the provider of electrons. A typical transistor operates with a collector current of 5 mA and a collector voltage of 6 volts, the power dissipated is 30 milliwatts.

D. Operation of vacuum tubes depends upon the flow of electrons from cathode to plate and the control of this flow b intermediate grids. Operation of the transistor is dependent upon electron and hole flow. These two devices perform the same functions, but there are considerable differences between the two. In order to appreciate these differences, a study of atomic structure, intrinsic materials, and electrical properties of semiconductors is required.

Review of atomic structure

A. Any atom may be considered to be composed of a centrally located nucleus surrounded by electrons, which spin in various orbits (see figure 1). The nucleus contains neutrons, which have no electric charge, and protons, whic are positively charged. Neutrons and protons have essentially the same weight, and the combined weight of all the neutrons and protons is referred to as the relative atomic weight of the element. The number of protons within the nucleus determines the atomic number of an element and the net positive charge on the nucleus. If an atom has the usual atomic number, but a different atomic weight because it contains an abnormal number of neutrons, it is called a isotope.



Picture of a lithium atom with an atomic number of 3.

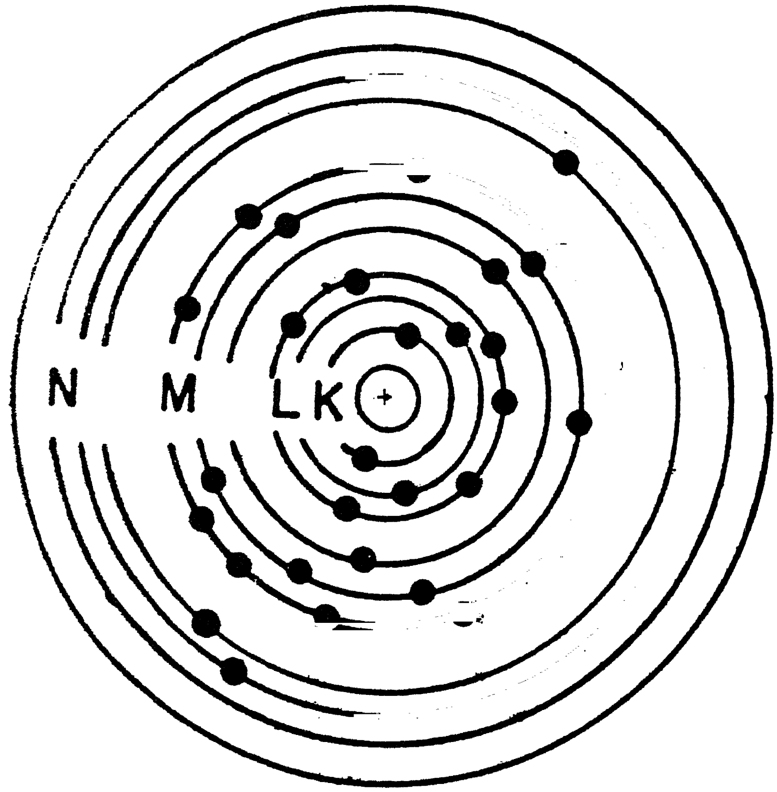
Figure 1.

B. In an electrically neutral atom, the number of electrons is equal to the number of protons, even though the proton is approximately 1,800 times heavier. If a neutral atom loses one or more orbital electrons, it becomes positively charged. If the neutral atom gains electrons, it becomes negatively charged.

C. An electron radiates electromagnetic energy if it jumps from some higher energy level to one which is closer to the nucleus. Conversely, an electron excited from an inner to an outer orbit will absorb energy. If by some means (intense electric fields, high temperatures, radiation, light, etc.) the total energy of an electron is increased, that electron will be torn from the parent atom. Under these conditions, ionization or breakdown has occurred.

D. Electrons have been found to surround the nucleus in shells as shown in figure 2 and the manner in which they are dispersed is:

Main Shell			Sub Shell	
1st Shell	K	2 electrons	2	electrons
			s	p
2nd Shell	L	8 electrons	2	6 electrons
			s	p d
3rd Shell	M	18 electrons	2	6 10 electrons
			s	p d f
4th Shell	N	32 electrons	2	6 10 14 electrons

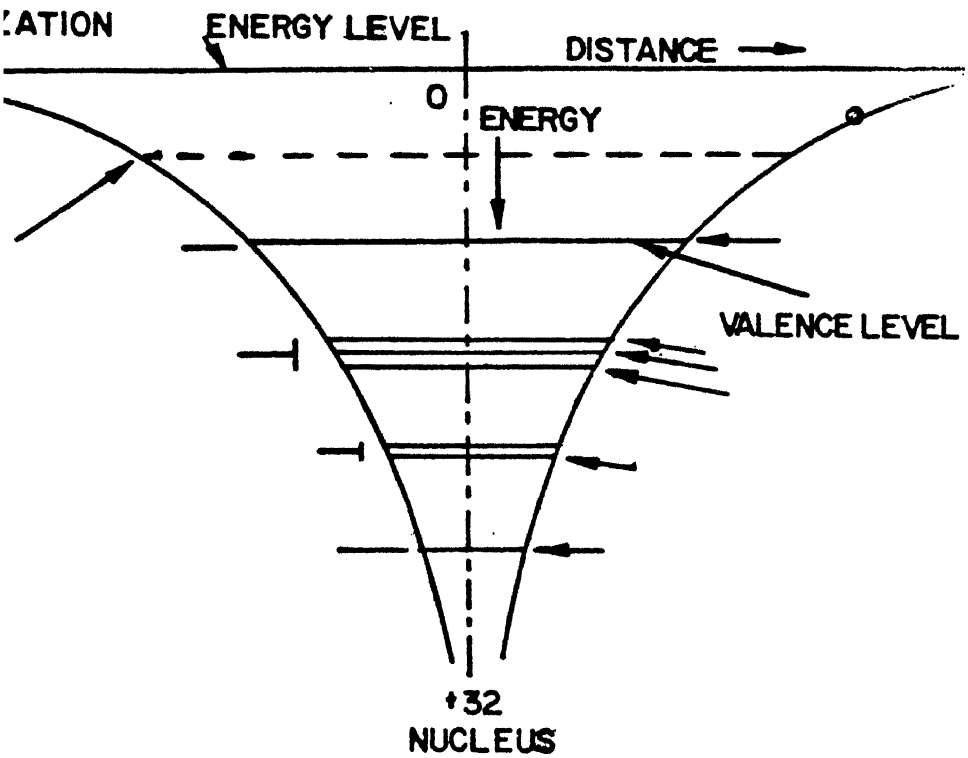


A two dimensional representation of the manner in which electrons are distributed about the nucleus of a germanium atom.

Figure 2.

E. Electrical and chemical activity of a material is restricted to the electrons in the outer shell. The outer shell of an atom is called the valence shell and electron occupying orbits in these shells are called valence electrons. Unfilled orbits lying above the valence orbit are called excitation levels. Imparting sufficient energ to an electron may cause it to jump into an excitation level. The applied electric field may cause them to drif by a displacement process toward the region of more positive potential. Actually, at temperature above absolute zero, there will be some probability of finding electrons in the excitation level because of thermal agitation. As we shall see later, this is one of the most serious problems encountered in the solid state art.

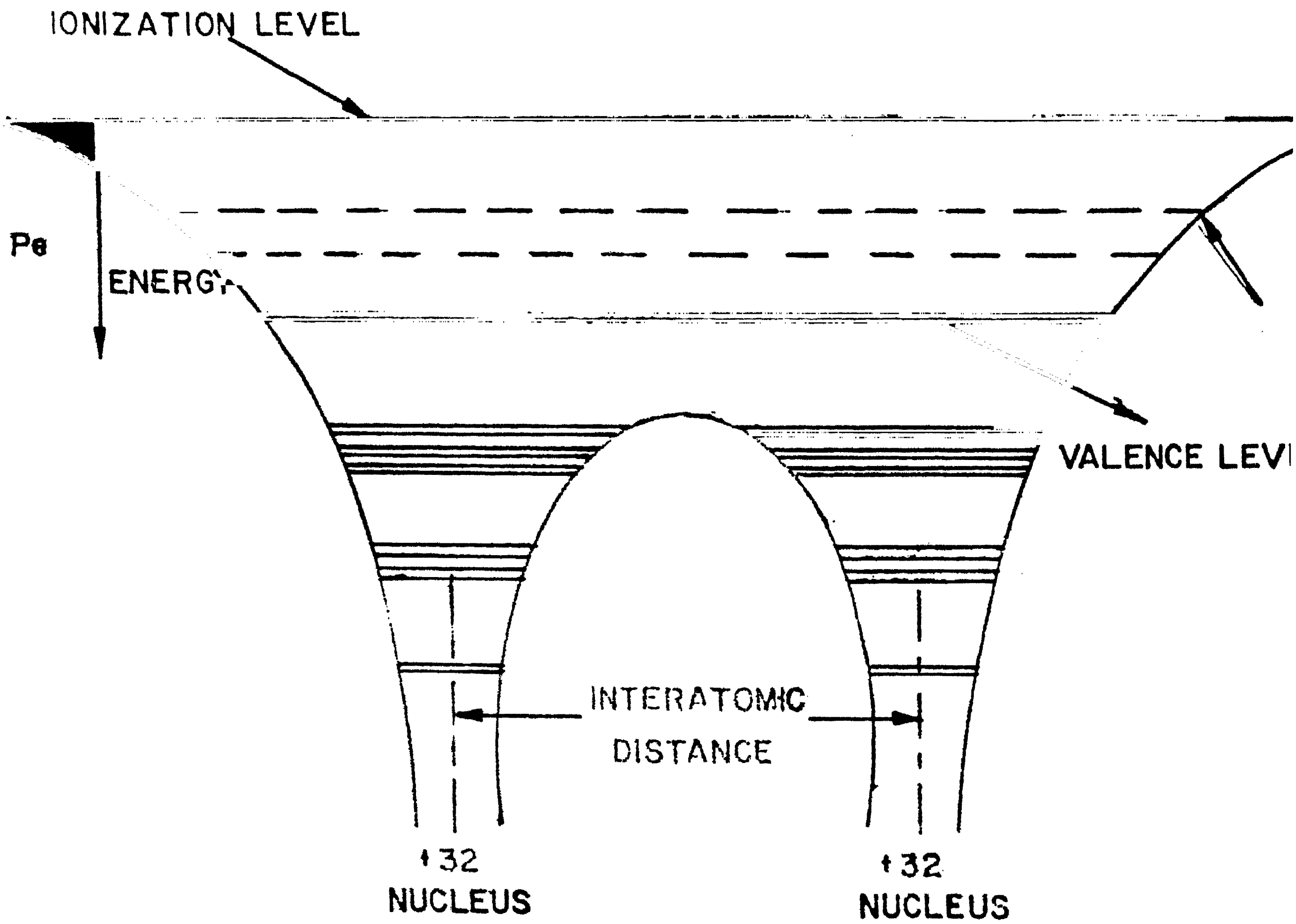
Since transistors are usually made of either germanium or silicon, let us investigte these elements. An unexcited germanium atom possesses 32 electrons, 28 of which are located within the first three completed energy levels leaving 4 electrons in the fourth shell; they are called valence electrons. Silicon has an atomic number of 14, which means there are 2 electrons in the K shell, 8 in the L, and 4 in the M shell; therefore, silicon has 4 valence electrons. A plot of the total energy of an electron as its distance from the germanium nucleus increases, is shown in figure 3.



Distribution of energy levels for a germanium atom.

Figure 3.

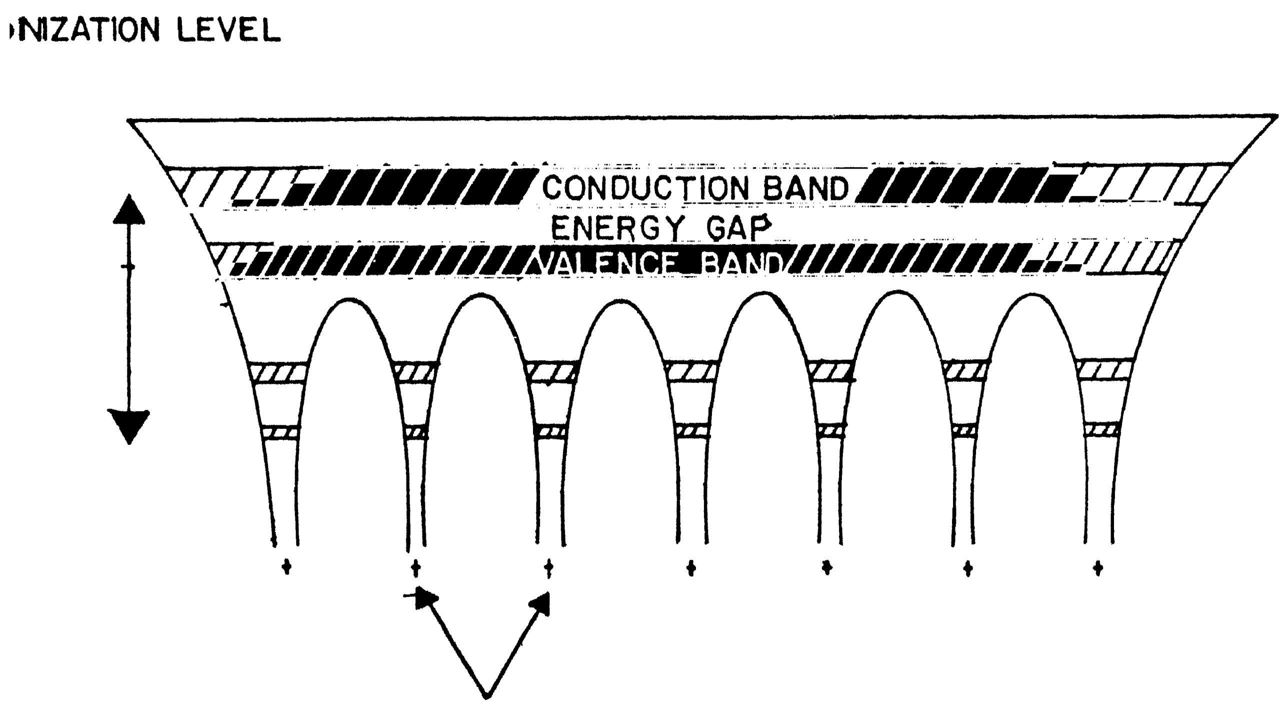
Now, if one germanium atom is brought into proximity with another, an interaction occurs which results in the formation of additional allowable levels for each atom. This must be true if no two electrons are allowed to occupy the same energy level in the whole system. In this way, when an electron in one atom is at a particular level, its counterpart in the other atom has a slightly different energy level, and they can switch levels continuously. Note in figure 4 that the valence and excitation levels are common to both atoms. This means a valence electron from atom could travel to another and vice versa without requiring any external energy.



When two similar atoms are brought together, an inner action occurs which permits additional levels.

Figure 4.

In a crystal where billions of atoms exist in close proximity and orderly array, the number of allowable energy levels is enormous. Instead of considering discrete levels, it is more convenient to speak of energy bands. An energy-band diagram for a crystal is shown in figure 5. The various valence levels form the valence band. The first excitation levels are lumped into the conduction band. For conduction to occur when an electric field is applied to the crystal of figure 5, electrons must be accelerated in order to change their total energy. But because of their discrete behavior their total energy can increase only if they can be excited into a new level. If, in a crystal, the valence band is completely filled, conduction can occur only when sufficient stimuli is impressed to raise some electrons from the valence band to the conduction band. Here there are many levels through which the electron may be accelerated. Note that accelerating an electron from the valence band into the conduction band leaves a vacant level in the valence band. This means that electrons can now accelerate in the valence band. The vacant level left in the valence band is a hole.



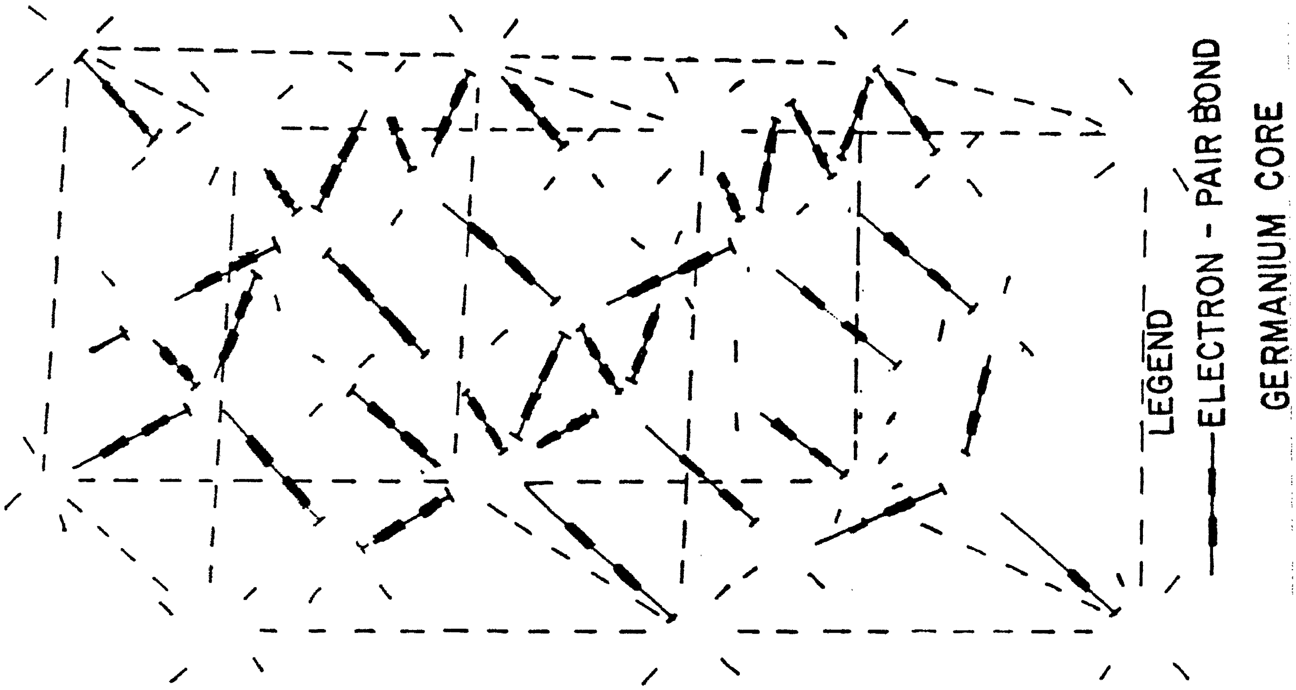
In a crystal, the splitting of energy levels form energy bands that represent a group of levels.

Figure 5.

G. Crystalline structures

1. The valence shell for a germanium atom contains 4 valence electrons. When germanium is in crystalline form the valence electrons in the outer ring of one atom align themselves with the valence electrons of adjacent atoms to form pairs of shared electrons. This electron sharing is called covalent bonding. These covalent bonds bind the germanium atoms into an orderly, geometric pattern within the crystal.

2. Figure 6 is a simplified illustration of the atomic arrangement of a crystal structure. The inert portion of each atom has an overall positive charge and is locked into the structure in an orderly manner. Each ion is repelled by the similarly charged surrounding ion from various directions, thereby stabilizing the positive of the ion in the structure. The relatively large mass of the ion also contributes to this stability.



Pure germanium crystal, lattice structure.

Figure 6.

3. Materials may be broadly classified as insulators, semiconductor, or conductors according to the energy in an electron must receive to jump the gap between the valence band and conduction band. Another method of classification is by the number of electrons in the valence shell.

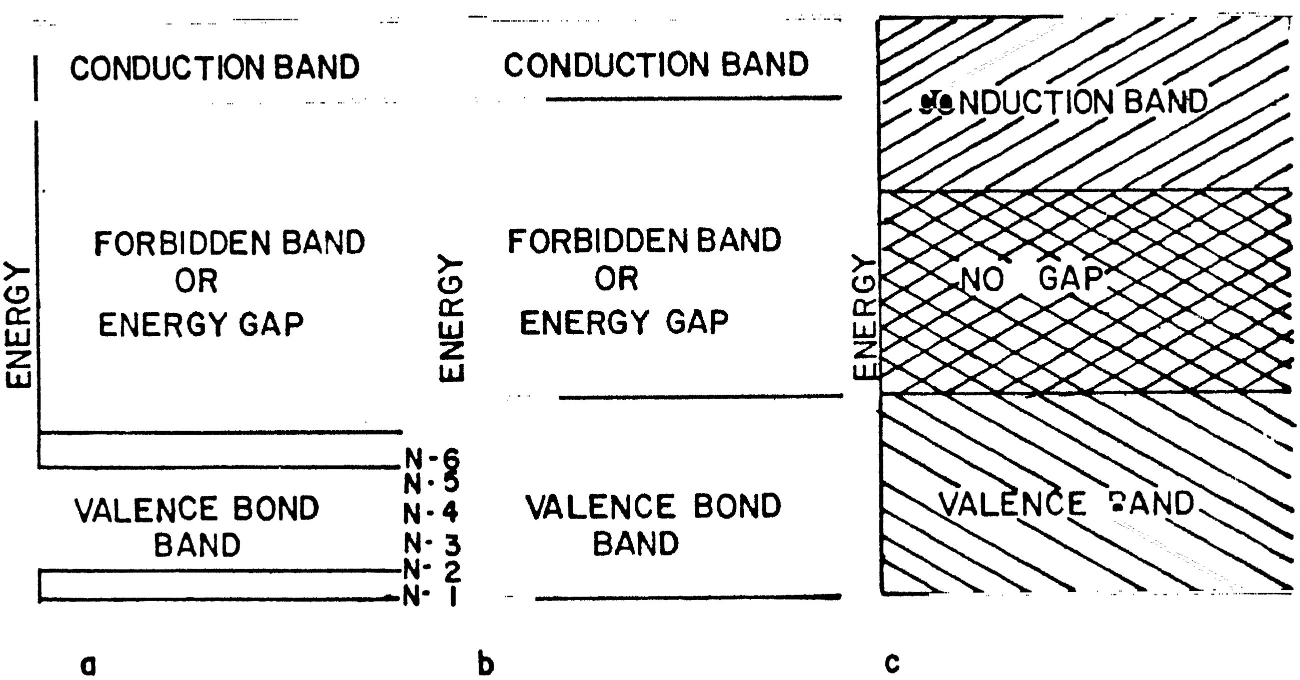
a. 1 to 3 valence electrons - conductor.

b. 4 valence electrons - semiconductor.

c. 5 to 8 valence electrons - insulator.

4. Insulators

a. An insulator may be defined as a material which offers high resistance to the flow of electrons. The basic reason for offering such a high opposition to the flow of electrons is that free electrons are relatively scarce in such materials. By referring to figure 7(a), which illustrates the energy diagram of an insulator's valence and conduction band, it can be seen that the energy gap is wider than that of the semiconductor and conductor. The energy levels within the insulator's valence band are filled, and the energy levels in the conduction band are empty. This means the valence electrons have very little opportunity to undergo changes from one valence energy to another.



Energy bands: (a) insulator (b) semiconductor (c) conductor

Figure 7.

b. Furthermore, the increment of energy required of a valence electron to be excited into the ionization level (bottom of the conduction band) is very large when compared to the thermal packages of energy (called phonons) which are available at room temperature. The probability of a valence electron becoming free is quite remote because of the large forbidden energy gap. Within the valence band, the electron motions are restricted to their orbital motions, and virtually no mobile electrons are available for participation in the conduction process.

5. Semiconductors--Figure 7(b) is the energy diagram of a semiconductor. The energy levels within the valence band are filled, as in the case of insulators. The valence electrons have very little opportunity to change levels in the valence band, since there are no vacant levels. The forbidden gap between the valence and conduction band is not as great as in the typical insulator. The probability of valence electrons acquiring the necessary increment of thermal energy is better, since smaller packages of thermal energy are required. This energy gap, at room temperature, is about 0.7 eV for germanium and 1.2 eV for silicon. Because of the lower height of the forbidden energy gap, semiconductors have resistivity lower than insulators, but considerably higher than conductors. An <u>electron volt</u> (eV) is the Kinetic energy acquired by an electron when accelerated through a one-volt potential difference.

6. Conductors - The energy diagram of a conductor is shown in figure 7(c). Notice the overlap between the upper valence levels and lower conduction levels. Valence electrons, in such a material, require very small increments of thermal energy to be excited into a conduction level. The probability of this action occurring at room temperature is very high, and the material displays low resistance (high conductivity)*. Such is the condition which exists in most metallic conductors.

*Conductivity is the reciprocal of resistivity; or, the ease with which a charge carrier can progress through a material.

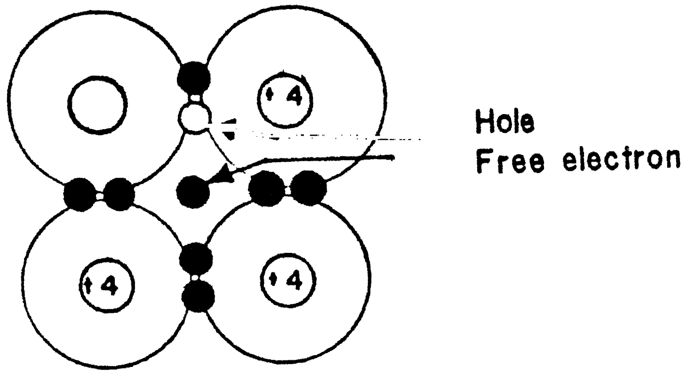
III. Intrinsic semiconductors

A. Semiconductor material which is very pure is called an intrinsic semiconductor. The nature of semiconductors is such that even very small amounts of certain impurities drastically alter their electrical properties. For this reason, a semiconductor would not be called truly intrinsic unless the impurity level is very small--for germanium less than 1 part impurity in 10^8 parts of germanium; for silicon, the impurity content would have to be less than 1 part in 10^{12}. In practice, however, semiconductor material with somewhat larger impurity concentrations than these is still sometimes referred to as intrinsic.

B. At temperatures of absolute zero, intrinsic germanium or silicon can be shown as it is in figure 6. All of the valence electrons are tightly held by the parent atoms and, also, through the covalent bonds by other atoms. The electrons are not free to move through the crystal structure and, thus cannot conduct electricity. For this reason, an intrinsic semiconductor at absolute zero behaves like an insulator. It is a very poor conductor of electricity.

C. Consider what happens as the temperature is increased. An increase in temperature means an increase in the heat energy of each atom. This increase in energy may be given to one of the atom's valence electrons. By this process, a valence electron may acquire sufficient energy to break away from its parent atom and, in so doing, break one of the covalent bonds. This electron is now free to wander through the crystal structure and is not bound to any particular atom. It is called a free electron and can now act as a current carrier if a voltage is applied to the material. A current carrier is simply any charged particle (such as an electron) which is free to move as part of an electric current if a source of voltage is applied.

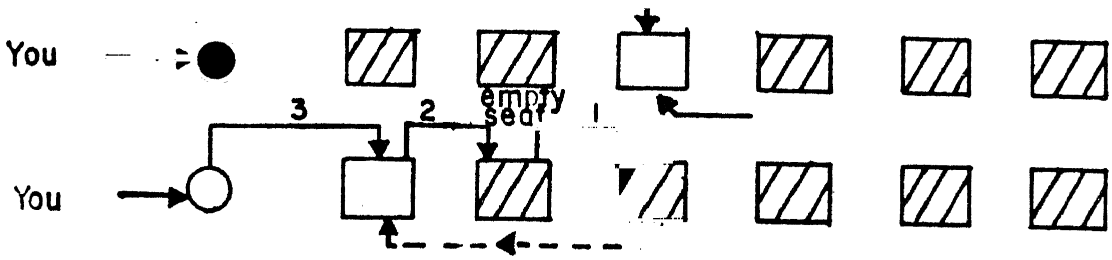
D. But what happened back at the place where the electron left its parent atom? It left behind a vacancy or an incomplete covalent bond, which is usually referred to as a hole. Figure 8 shows the crystal structure with one free electron and one hole brought about by the electron breaking away from the parent atom. This process of the formation of free electrons and holes is called thermal generation.



Creation of a free electron and a hole caused by an increase in crystal temperature.

Figure 8.

E. The interesting thing about a hole is that it can act as a current carrier. If a hole is created by an electron breaking away in one atom, an electron from a neighboring atom can easily fill the hole by breaking its own covalent bond and jumping over to the first atom. When this occurs, it appears that the hole has moved. If you have a hole at A and an electron at B, when the electron fills the hole at A, it leaves a hole at B. Thus, in effect, the hole has moved from point A to point B. This can be illustrated by considering the situation when you arrive late at the theater and find the only vacant seat is in the center of the row (see figure 9).

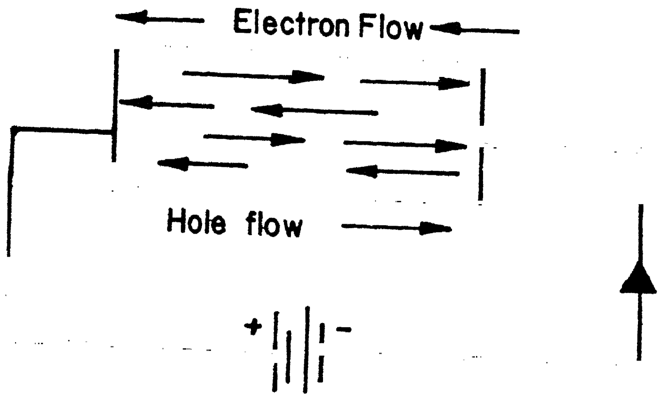


Hole movement.

Figure 9.

Either you can become a "free electron" and go along the row until you get to the "hole" or the people in the first two seats can move in sequence one seat to the right and make the "hole" move to you at the end of the row.

F. Anywhere a hole exists there is a net positive charge because the +4 charge of the parent atom (nucleus and inner-orbit electrons) is greater than the -3 charge of the three remaining electrons. Thus, we consider the hole as having, in effect, a positive charge. When the hole moves, there is a flow of positive charge. A voltage is applied to a semiconductor containing free electrons and holes, the free electrons will move from negative to positive, and the holes will move from positive to negative. Remembering the discussion of hole movement, you can see that a hole moving to the right is really an electron moving to the left. Thus, the flow of holes from positive to negative is really the same as the flow of negative charges (electrons) from negative to positive. You can think of current in a semiconductor as consisting of two parts; free electrons moving in the opposite direction. To get the total current, you must add the two parts. Figure 10 is a representation of the flow of charges in a semiconductor.



The flow of charges in a semiconductor due to an applied voltage.

Figure 10.

The flow of charges in a semiconductor due to an applied voltage. NOTE: There is no hole flow external to the semiconductor. Current flow in a conductor is by the movement of free electrons.

You may be wondering what happens to the holes when they reach the edge of the piece of semiconductor material (point B in figure 10). The answer is that some of the electrons coming from the negative battery terminal combine with or fill tne holes so that both the holes and the filling electrons disappear as charges. This process is called recombination. The rest of the electrons travel through the semiconductor as free electrons. The electrons leaving (at A) fall into one of the two categories: those which entered at B and traveled through the crystal or those which were freed within the crystal when the holes were formed.

G. It is very important for you to understand that, even though hole current is actually due to the movement of electrons, it is not the same type of electron motion which makes up the free electron current. The electrons, which cause the hole current, jump from hole to hole and do not have enough to become really free. On the other hand, the free electrons have enough energy to move freely through the crystal without being tied down to any atom.

H. You can see from this that the free electrons are able to move faster through the crystal than the holes, which have to move in a succession of jumps. We sa' that the free electrons have a higher mobility than the holes.

I. At ordinary room temperature (approximately 25°C), the thermal energy is sufficient for a large number of free electrons and holes to exist in an intrinsic semiconductor. At room temperature intrinsic semiconductors such as germanium and silicon are fair electric conductors, being much poorer conductors than a metal such as copper, but much better conductors than an insulator such as rubber. An important characteristic of an intrinsic semiconductor is that is possesses a negative temperature coefficient (resistance decreases with a rise in temperature); therefore conductivity increases with an increase in temperature. This is true because of the increased thermal agitation at higher temperatures; therefore, there are more free electrons and more holes created. In an intrinsic semiconductor with no applied voltage, the total number of free electrons equals the total number of holes.

IV. Doped (extrinsic) semiconductors

A. Practical semiconductors contain traces of impurities deliberately added to the material after the natural impurity level has been reduced to a negligible degree. The types of added impurities fall under two categories:

1. Elements containing five valence electrons (Pentavalent)

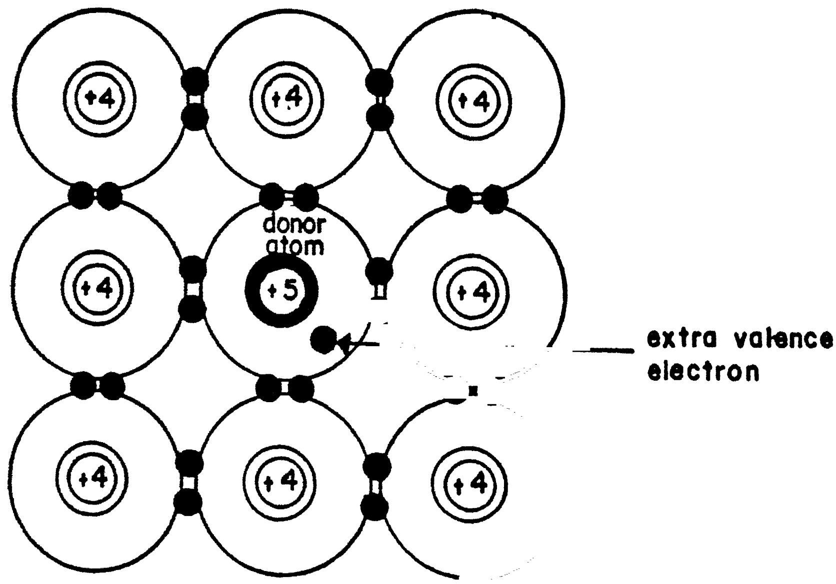
2. Elements containing three valence electrons (Trivalent)

The effects of each type upon the energy and electrical characteristics of germanium will be examined.

B. The donor or N-type crystal

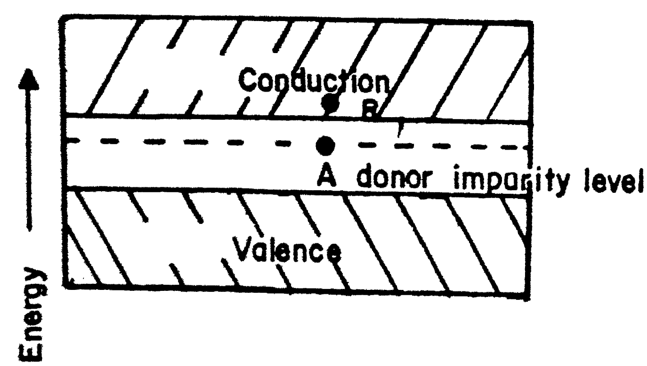
1. There are a number of elements possessing five electrons in their outermost shells which are chemically compatible with germanium. Arsenic is a typical example and is used in our discussion. The arsenic atoms occupy positions in the lattice structure, as illustrated in figure 11. Four of the outer-shell electrons engage in the formation of covalent bonds with the electrons of

neighboring germanium atoms, thereby completing these bonds. The fifth outer electron of the arsenic atom, finding no vacancy in the lattice, is left out of locked arrangement. This results in the fifth electron being loosely held to its nucleus even at very low temperatures; it is, in effect, at an energy level above the valence band but below the conduction band (see point A of figure 12).



The additon of an N-type impurity atom produces one free electron.

Figure 11.



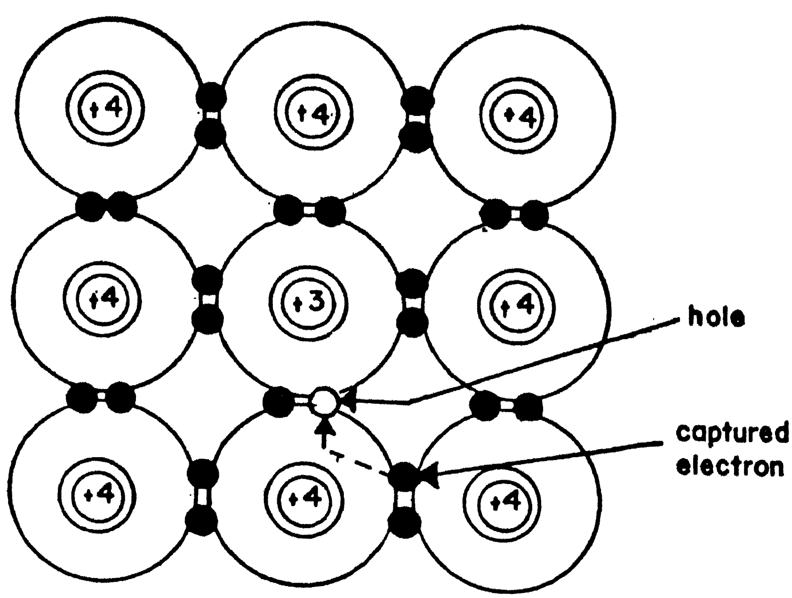
Energy distribution in donor-type germanium.

Figure 12.

2. There is one electron in such a state for each arsenic atom in the lattice. The energy gap between the energy level of the fifth electron and the conduction band is 0.01 eV. The probability of the fifth electron being free at room temperature is very great, since room temperature is approximately 0.026 eV.

3. A crystal containing an impurity whose atoms possess five valence electrons is called a donor crystal, since it readily donates electrons to the conduction process. The conduction which occurs because of these mobile electrons, when an external electric field is applied, is called extrinsic conduction, as opposed to intrinsic conduction which is due to electrons that are elevated to the conduction region from the valence energy band. Because of the great difference in energy requirements between the two types of conduction, extrinsic conduction occurs at a much lower temperature than intrinsic conduction (where the increment of energy must be at least as high as the forbidden energy gap). At a given temperature the conductivity of the donor crystal is higher than that of a pure crystal to an extent determined by the number of impurity atoms added. The major carriers of charge in this type of material are negative, hence the term N-type crystal.

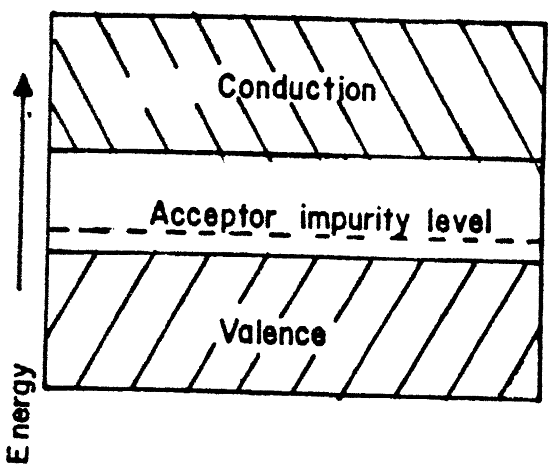
V. The acceptor or P-type crystal



The addition of a P-type impurity atom produces a vacancy in the covalent bond (hole).

Figure 13.

A. Figure 13 illustrates the lattice structure when a small percent of the element gallium is added to the purified crystal. Gallium has three valence electrons, leaving one of its covalent bonds incomplete at very low temperatures. At room temperature, the gallium atom readily captures an electron from another atom to complete its covalent bonding arrangement, and any such three-valence elements are called "acceptor" atoms. When the gallium atom has acquired one more electron than it should normally have, it becomes a negative ion. This extra electron must beat a greater distance form the gallium nucleus than the normal three-valence electrons and is therefore closer to the conduction band in terms of energy. The energy level of the acquired electron is immediately above the valence band, as shown in figure 14.



Energy distribution in acceptor type germanium.

Figure 14.

B. Notice that only a small increment of energy is required (0.01 eV) to excite a valence electron into the acceptor impurity energy, since this level is closer to the valence band than the conduction region. This action usually occurs even at low temperatures, where relatively few valence electrons are thermally excited across the entire forbidden energy gap. Each valence electron excited into the acceptor impurity level leaves a vacancy (hole) in the valence energy band, so it is possible for valence electrons to leave one covalent band and move to another with the help of an ex ternally applied electric field.

C. With the application of an external electric potential, the valence electrons are encouraged to move from vacancy to vacancy in a direction toward the positive side of the external potential. It should be noted that a valence electron creates a hole when it moves on to fill an adjacent hole, so that the number of holes is constant and determined by the number of acceptor impurity atoms present in the lattice. As valence electrons are drifting, the holes are drifting toward the negative terminal of the external potential. Within the extrinsic range of temperatures, at which intrinsic conduction is negligible, the significant portion of conduction occurs by this hole current in the P-type semiconductor. Actually, the major cariers of charge in this material are positive, hence the term P-type semiconductor.

VI. Some electrical properties of semiconductor materials

A. Resistivity

1. The electric resistance of a piece of material depends on its atomic structure; on the material length; and on its cross-sectional area. Resistance can be expressed mathematically as:

$$R = \frac{PL}{A}$$

where R, L, and A are resistance, length, and cross-sectional area, respectively, and P is the resistivity (specific resistance) of the material. The reciprocal of resistivity is conductivity. Resistivity is a measure of the degree that a material opposes the flow of electric current, and conductivity is the degree that a material allows current to flow. A material which exhibits a high opposition to current flow is said to have a high resistivity. The same material could also be said to have a low conductivity.

2. The manner in which a semiconductor device behaves in an electronic circuit depends greatly on its resistivity, which can be controlled over a wide range. The value of resistivity (or conductivity) of a semiconductor depends on: the charge on each carrier; the concentration of current carriers (holes and electrons); and the carrier mobility (ease with which carriers may be moved).

3. The charge on a hole is always +1 and the charge on a free electron is -1. These values cannot be changed. Thus, carrier concentration and carrier mobility are the properties that may be changed to alter resistivity. In general, it is desirable to make carrier mobility as high as possible. This leaves carrier concentration as

the property that can be adjusted to control resistivity. Carrier concentration, or carrier density, is measured in holes or electrons per cubic centimeter, whichever carrier is the majority carrier. You will recall that for an intrinsic semiconductor the number of free electrons is equal to the number of holes. The value of the free-electron concentration (or hole concentration) in an intrinsic semiconductor is called the intrinsic carrier concentration. This value increases exponentially with an increase in temperature.

B. Thermal generation and recombination

1. When a semiconductor is exposed to a temperature above absolute zero, some of the heat energy added to the material may be acquired by an electron, raising it to the conduction band and leaving behind a hole. This produces two charge carriers: one hole and one free electron. They are said to have been thermally generated. As long as the material is exposed to this temperature, the free electrons and holes present are i continuous random motion even though there is no net current flow.

2. This may be likened to a swarm of bees around a hive. Each bee moves rapidly from place to place in the swarm but if no new bees are arriving and none are leaving, the net flow of bees is zero, although they are all in continuous motion.

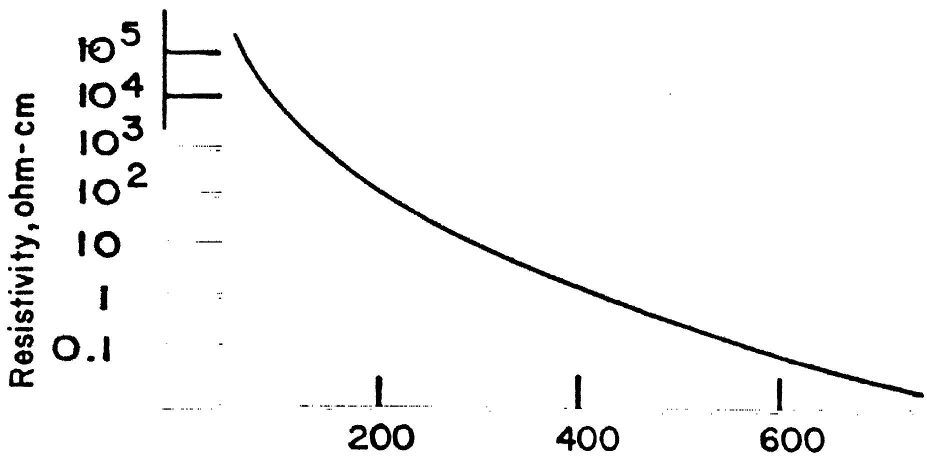
3. The rate at which hole-electron pairs are thermally generated depends on the temperature and on the width of the forbidden energy gap in the crystal. You will recall that germanium has a smaller energy gap than silicon. Consequently, at a given temperature, the thermal generation rate will be higher in germanium tha in silicon, because it takes less energy to move an electron from germanium's valence band to its conductio band.

4. As a free electron moves randomly through the crystal structure, it may encounter a hole and become a bound valence electron. When the electron combines with the hole, the hole no longer exists and the electron is no longer free; hence, two carriers cease to exist. This process is called recombination.

5. The rate at which recombination takes place depends on the number of holes and free electrons in the material. When the rate at which the hole-electron pairs are thermally generated equals the rate at which the hole-electron pairs recombine, the material is said to be in thermal equilibrium.

6. Recombination rate may be higher in one material than in another even though both materials have the same concentration of holes and free electrons. High recombination rates can be caused by certain types of impurities in the crystal and imperfections in the crystal structure. Temperature also has an effect on the recombination rate.

7. Resistivity will decrease (conductivity will increase) when more carriers are present to conduct current. Since intrinsic carrier concentation increases with temperature, resistivity decreases, and conductivity increases. A typical plot of intrinsic resistivity versus temperature is shown in figure 15.



Variation of resistivity with tempeature for intrinsic silicon.

Figure 15.

8. In extrinsic semiconductors, the number of free electrons is not equal to the number of holes. In N-type materials, each donor atom contributes a free electron without contributing a hole. The only holes present are those produced by thermal generation. The thermally generated holes are called minority carriers. Similarly, in P-type materials, the only free electrons present are those thermally generated, and the number of holes present is equal to the number created by the acceptor impurity plus the number generated. The thermally generated electrons are called minority carriers.

9. In an extrinsic semiconductor, the current carriers due to the added impurity greatly outnumber the thermally generated carriers. For example, in N-type silicon suitable for transistor fabrication, there may be 100,000 electrons from the temperature. Since the resistivity of this extrinsic material does not change rapidly with temperature over the normal temperature range. However, if the temperature is greatly increased, the concentration of thermally generated carriers may become comparable with that of the impurity-produced carriers, and the resistivity will become temperature-dependent. If the temperature of the semiconductor is increased to such an extent that the thermally generated carriers greatly outnumber the impurity-produced carriers, properties of the material will be mainly dependent on the internal thermally generated carriers, and the material will become intrinsic.

10. Resistivity of extrinsic germanium or silicon at room temperature is determined almost completely by the amount of impurity present in the material. Within limits, any desired value of resistivity can be obtained by adding the correct amount of impurity during formation of the crystal.

C. Mobility

1. It hs been stated that mobility is a measure of the ease with which the carriers can be made to move in a material. It is measured as the rate of movement of the carrier (in centimetes per second) per unit potential field (1 volt per centimeter). Thus, mobility has the dimensions centimeters per second dividend by volts per centimeter, or cm^2/volt-sec.

2. Although mobility does not appear to be very significant from resistivity considerations, it plays a very important role in the behavior of semiconductor devices. In semiconductors, the mobility of the electrons is greater than the mobility of the holes, simply because it is easier to move a free electron in the conduction band than it is to move a bound electron into a hole in the valence band. (Keep in mind that the movement of electrons in the valence band from hole to hole is what brings about the movement of holes.) Since the holes can be made to move by the application of a voltage, the idea of "hole mobility" is not unreasonable.

3. Carrier mobilities in germanium are much higher than the corresponding mobilities in silicon. Table 1 shows the intrinsic properties of the two materials at room temperature.

PROPERTY	GERMANIUM	SILICON	VOLT
Electron Mobility	4,000	1,400	cm^2/volt-sec
Hole Mobility	1,900	500	cm^2/volt-sec
Intrinsic Resistivity	65	200,000	ohm-cm
Energy Gap	0.7	1.1	eV

Intrinsic properties of Germanium and Silicon at room temperature.

TABLE 1.

4. Although several factors affect the carrier mobilities, the nature of the crystal structure through which the carriers move has the predominat effect. Any impurities or imperfections in the crystal lattice tend to retard carrier motion. If the structure is perfectly regular, all atoms are in their proper places and no extra atoms are present. The carriers can move easily through the structure and mobility is high. However, if imperfections exist in a crystal, the movement of carriers is retarded and mobility is reduced. The types of imperfections that can exist in a crystal structure are far too numerous to delve into at this time. Suffice it to say that one of the most important steps in the manufacture of semiconductor devices is the forming of crystals with as nearly perfect lattice structure as possible.

5. Temperature is another factor that affects mobility. At low temperatures, atoms in the crystal structure tend to stay in their regular places. As temperature is increased, energy is added to the crystal. Some of this energy is used to excite the electrons to the conduction band, but some of it is also given to the atomic cores, causing them to move very slightly. Although the cores do not move away from their positions, they do vibrate in and out of position much as a violin string vibrates without leaving the violin. This vibration has the effect of impeding carrier motion.

6. The higher the temperature becomes, the more intense the vibrations become and the lower the mobility becomes. Since these vibrations are small at moderate temperatures, the effect of temperature on mobility does not change greatly over the normal operating temperature of most semiconductor devices. For intrinsic germanium and silicon, temperature has a greater effect on carrier concentration than it has on mobility.

D. Diffusion currents

1. It has been determined that if a voltage is applied to a piece of semiconductor material, the holes move to the negative terminal and the electrons to the positive terminal. The combined effect of this motion of holes and electrons constitutes a current.

2. It is possible for a current to flow in a semiconductor even in the absence of an applied voltge if a concentration gradient exists in the material. A concentration gradient occurs when the concentration of one type of carrier is greater in one part of a semiconductor than it is in some other part.

3. When a concentration gradient of carriers (either holes or free electrons) exists in a material, the carriers tend to move from the region of higher concentration to the region of lower concentration. The carriers are said to diffuse from the region of high concentration, and the current produced by this movement of charge is diffusion current.

4. Consider a small bar of P-type semiconductor material in which the charges are evenly distributed along the length of the bar. The concentration of holes and free electrons are in equilibrium and no gradient exists. Suppose that a large number of electrons (minority carriers) is injected at one end of the bar. (How this is accompolished will be discussed in PN Junction theory.) These added minority carriers cause a higher concentration of electrons at the end where they are injected than in the rest of the bar. Hence, an electron gradient exists. The excess electrons will diffuse toward the other end of the bar, attempting to come to a uniform distribution throughout the bar. Their motion results in a diffusion current. The rate at which the electrons diffuse, and hence, the diffusion current depends on the value of the gradient and on the mobility of the electrons.

5. This might be compared to a car rolling down a hill. The rate at which it comes down the hill depends on how steep the hill is (gadient) and how easy the car is to move (mobility). A similar reasoning applies when the excess carriers are holes.

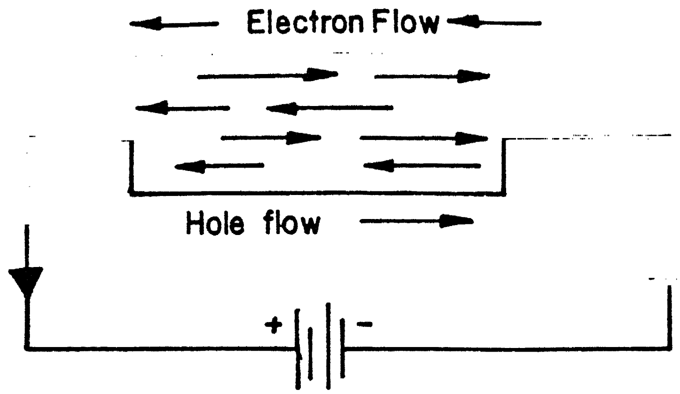
6. Presence of excess carriers increases the recombination rate in a semiconductor material. Eventually, the excess carriers disappear by recombination. The length of time required for the excess carriers to disappear by recombination is called the Lifetime of the excess carriers.

7. We have seen that two distinct things occur when excess minority carriers are injected into a material. The carriers diffuse and they recombine with the opposite-type carriers. Consider these two occurrences simultaneously. Imagine, again a high concentration of free electrons injected at one end of a P-type semiconductor bar. The electrons diffuse toward the other end of the bar and, at the same time, recombine with holes. As they move along the length of the bar, more and more of them disapper by recombination. Eventually, all of the excess electrons will disappear, but in the meantime they have moved along the bar; the distance the electrons move before they disappear is called the diffusion length of minority carriers. If excess holes are injected into an N-type material, the holes will undergo the same sort of process as free electrons.

8. You can see that the diffusion length of minority carriers in a material depends on how fast the carriers move and on how long they move before disappearing; that is, diffusion length depends on mobility and lifetime.

VII. Formation and behavior of the PN junction

A. It has been brought out in the information sheet, "Introduction to Semiconductors," that when a voltage is applied to a semiconductor, current flow is brought about as a result of holes moving toward the negative terminal and electrons moving toward the positive terminal (see figure 16).



The flow of charges in a semiconductor
due to an applied voltage.

Figure 16.

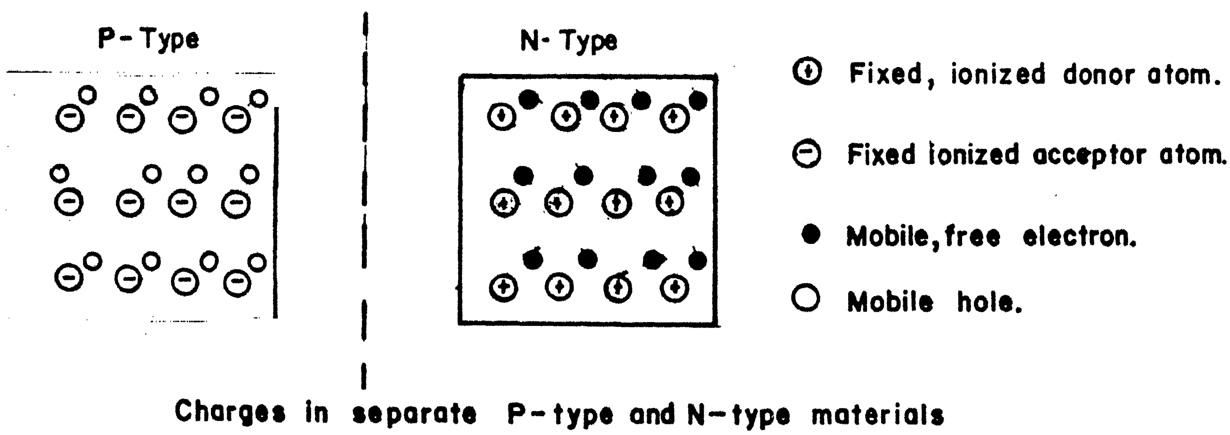
The total current is the sum of the current produced by the hole flow and the electron flow. It is considered a single current. A second current may exist in a semiconductor. This current, called diffusion current, comes about as a result of a gradient of a carrier concentation. The diffusion current may also be due to both hole and electron flow. The hole and electron flow is in opposite directions and the total diffusion current is the sum of the two.

B. A material which contains an equal number of positive and negative charges is said to be electrically neutral. Objects which are electrically neutral do not attract electric charges. An ordinary atom is electrically neutral since it has as many negative charges (electrons) as it has positive charges (protons). When an atom loses an electron, it is left with a net positive charge and is called a positive ion. When an atom gains an extra electron, it has a net negative charge and is called a negative ion.

C. A sample of semiconductor material is normally electrically neutral since it is made up of atoms which are themselves electrically neutral. Although a free electron may "wander" away from the atom (leaving a positive ion), it is still inside the semiconductor material, the semiconductor remains electrically neutral. If a current flows in a semiconductor due to an applied voltage, electrons are continually leaving the material at the positive terminal and at the same time electrons are entering (at the same rate) at the negative terminal. The semiconductor remains electrically neutral during conduction when considered as a single unit. However, if for some reason, a semiconductor loses electrons without regaining an equal amount, it will be left with a

net positive charge. Likewise, if it should gain positive charges without losing an equal amount, it will be positively charged. On the other hand, if it should gain extra electrons or lose positive charges, it will become negatively charged. When an object becomes positively charged and another object becomes negatively charged, a potential difference (or voltage) will exist between them.

Consider an N-type semiconductor such as silicon. Each silicon atom consists of a core with a net charge of +4 and four valence electrons, each with a charge of -1. Thus, the silicon atom is electrically neutral. Each donor atom has a core with a net charge of +5 and five valence electrons each with a charge of -1. Only four of these valence electrons are used in bonding with the silicon atoms. The fifth electron is free to wander around. As it moves away from the donor atom, it leaves behind a positive ion with a net charge of +1. The positive ion is not free to move, as it is fixed in the crystal structure. Thus, an N-type semiconductor is studded with immobile positive donor ions and mobile negative electrons. In a similar way, P-type silicon may be regarded as a neutral material studded with immobile negative acceptor ions and mobile positive holes. Figure 17 illustrates the charge distribution in separate P-type and N-type samples.



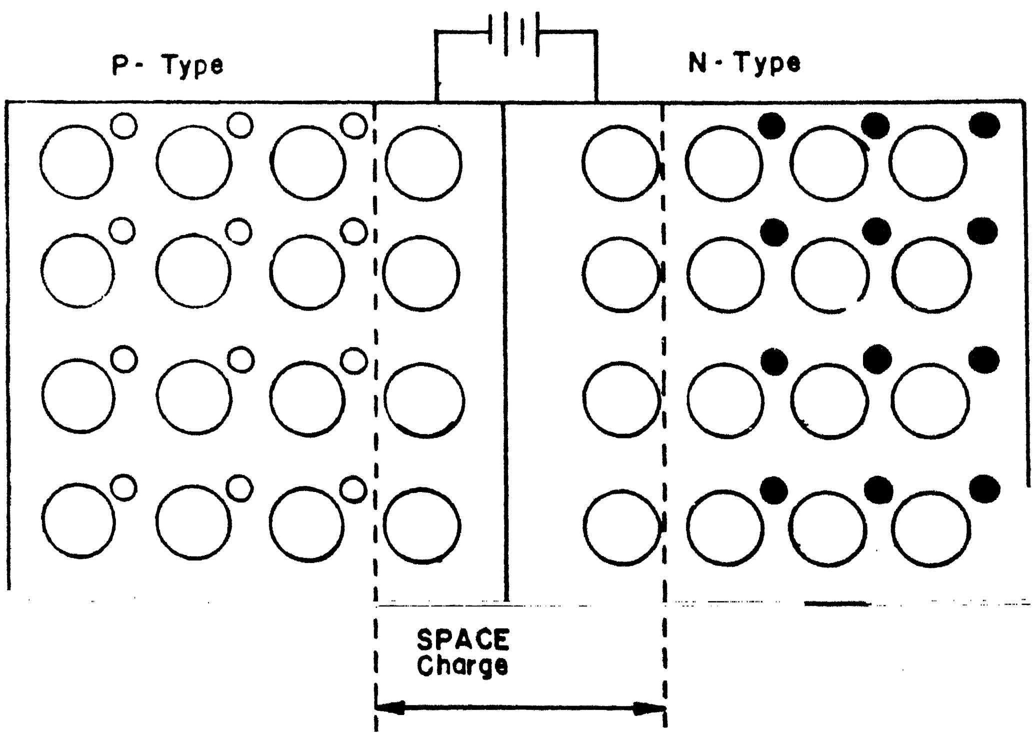
Charges in separate P-type and N-type materials.

Figure 17.

The silicon atoms are not shown and should be imagined as a continuous crystal structure over the whole background. The immobile ions will be regularly distributed in the crystal structure; but the holes and electrons being free to move, may be randomly distributed at any moment.

By themselves, the separate P and N materials are of little practical use. However, if a junction is formed consisting of a piece of P-type material joined to a piece of N-type material so that the crystal structure is unbroken, a device is produced which is extremely useful. We call such a device a "diode" and its usefulness stems from the fact that it will allow current to flow through it in only one direction.

E. We now turn to the condition of the materials at the instant the junction is formed. (We shall take the liberty of assuming that we can merely push the two pieces together to form the junction.) A completely different set of conditions will now exist. In the P region, there is a high concentration of holes. Since the hole concentrtion on the P side is so much greater than that on the N side, the holes will diffuse into the N region. The diffusion mechanism is similar to the uniform distribution of ink molecules in a glass of water after an ink drop has been introduced. The ink molecules try to distribute themselves uniformly. In technical parlance, we say that a hole concentration gradient exists from the P to N region. Similarly, an electron concentration gradient exists from the N to P region and results in electrons diffusing across the junction. See figure 18.



Changes in an unbiased PN junction.

Figure 18.

F. At first glance, it would seem that the holes and electrons would keep diffusing across the junction and recombine with each other until no current carrier remained or until just one or the other kind of charge carrier remained. However, this is not the case. For each hole that crosses the junction from the P to the N side, there remains an unneutralized immobile negative ion on the P side. Similarly, each electron that crosses from the N to the P region leaves an unneutralized positive ion. These unneutralized, immobile ions on each side of the junction are called uncovered charges, and the electric field between them can be conveniently represented by a battery placed across the junction as shown by the dashed lines in figure 18.

G. The holes that cross from the P to the N region recombine with electrons on the N side. Simarly, electrons from the N region recombine with holes on the P side. This flow of holes from the P to N side and electrons from the N to the P side constitutes a recombination current across the junction. This recombination current does not, however, persist at some constant value. Instead it falls to some very low value vicinity of the junction. The uncovered negative ions on the P side start repelling the electrons from the N side while the wall of uncovered positive ions on the N side repels the holes from the P side. The battery in figure 18, therefore, represents the barrier potential set up by the uncovered charges, which inhibits the recombination currents. Thus, it seems that a condition of equilibrium is established between the diffusive potential of the concentration gradient, the barrier potential of the concentration gradient and the barrier potential of the uncovered charges.

H. If thermal agitation caused all the mobile carriers to have exactly the same kinetic energy, this simple explanation for equilibrium conditions at the barrier would suffice. However, the thermal energy impaired to the mobile charge carriers is randomly distributed. Statistically speaking, some holes and electrons have only a small amount of kinetic energy whereas others have a very large amount. Some of the high energy carriers will, from time to time, be capable of overcoming the barrier potential. If this were the only action, it would seem that the barrier height would keep increasing in an effort to compensate for those high-energy carriers that manage to hurdle it. Ultimately, we might expect the last of the mobile charges to cross the barrier, leaving some large barrier potential.

I. This is an incomplete, although improved, picture of conditions at the junction. The thing we are neglecting is that no material is perfectly P or N. The P material will have some free electrons in it caused by the breaking of covalent bonds by thermal agitation. The hole which is produced is no different from any other hole in the P side, where holes are obviously the majority current carriers. The electron in the P material constitutes a minority carrier, and it will have some average time of life (called lifetime) before it combines with one of the numerous holes available. The lifetime of a minority carrier clearly depends upon the number of surrounding majority carriers which, in turn, is determined by the number of impurity atoms introduced into the lattice.

J. If this electron in the P region survives long enough to drift into the vicinity of the junction, it will come under the influence of the electric field existing there. The direction of the field is such that the electron will be swept across the depletion region (region containing the uncovered charges) since it is attracted by the uncovered positive ions on the N side. Another way of visualizing this is to imagine the barrier battery in figure 18 forcing electrons from the P to the N side.

K. By similar reasoning, we see that a thermally generated hole in the N material constitutes a minority carrier that would be swept across the depletion region from the N to the P side. The flow of thermally generated minority carriers across the junction is aided by the potential barrier.

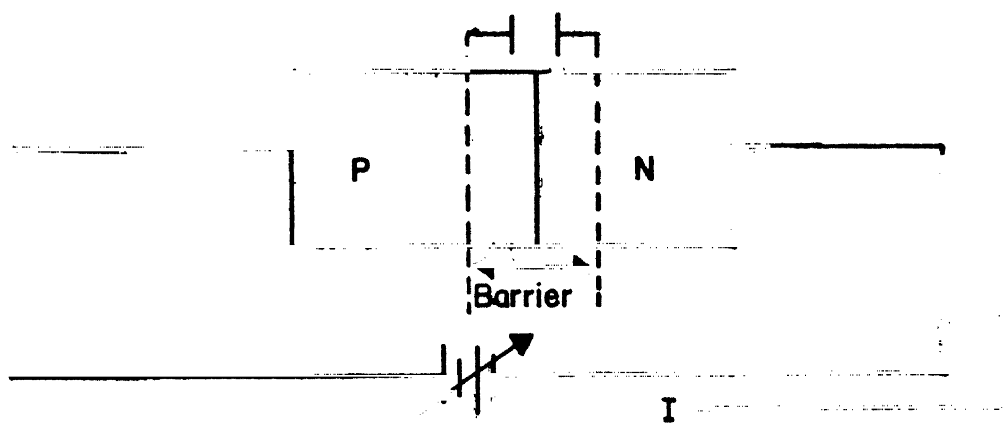
L. We now have a complete picture. With no external voltage applied, the actual equilibrium conditions are as follows: There will be a net recombination current across the junction which consists of holes climbing the barrier from the P to the N side and electrons which climb the barrier in the opposite direction.

M. At the same time, the breaking of covalent bonds will cause a net thermally generated current because the minority carriers are swept across the barrier. The thermally generated current (minority) depends solely upon temperature. The net result is that the total junction current is zero, which it must be, since shorting a PN junction with a piece of wire does not result in a current flow through the wire. The barrier height will assume a potential of such value that it permits the recombination current to just equal the thermally generated current.

N. If the amount of impurities added to the semiconductor material to start with is increased, the potential barrier will be higher and not extend as far into the P and N regions. This is due to the mobile carriers not going as far or deep into the materials and the height of the barrier will be higher due to the increased concentration of donor and acceptor atoms. Overall, the barrier will become narrower.

VIII. Forward bias

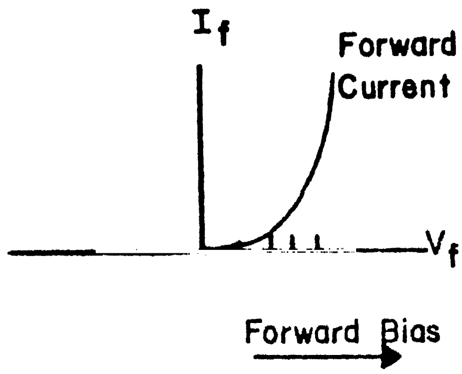
A. Consider that an external source of potential is connected to the PN junction, as illustrated in figure 19.



The PN junction with forward bias permits large amounts of current to flow.

Figure 19.

Placing the voltage source across the diode causes an electrical field which opposes the barrier potential (positive to P-type and negative to N-type material) to be established through the semiconductor. This is known as forward bias. The net effect is that the height of the barrier is reduced. For convenience, we might think of the external source as trying to push holes from the P to the N region and electrons from the N to the P region. The actual mechanism involved is, however, not one of pushing but merely controlling the net barrier potential. If we vary the source from one potential to a higher potential, we shall find that the current increases quite rapidly along some exponential curve. (Refer to figure 20.)



Forward bias characteristics.

Figure 20.

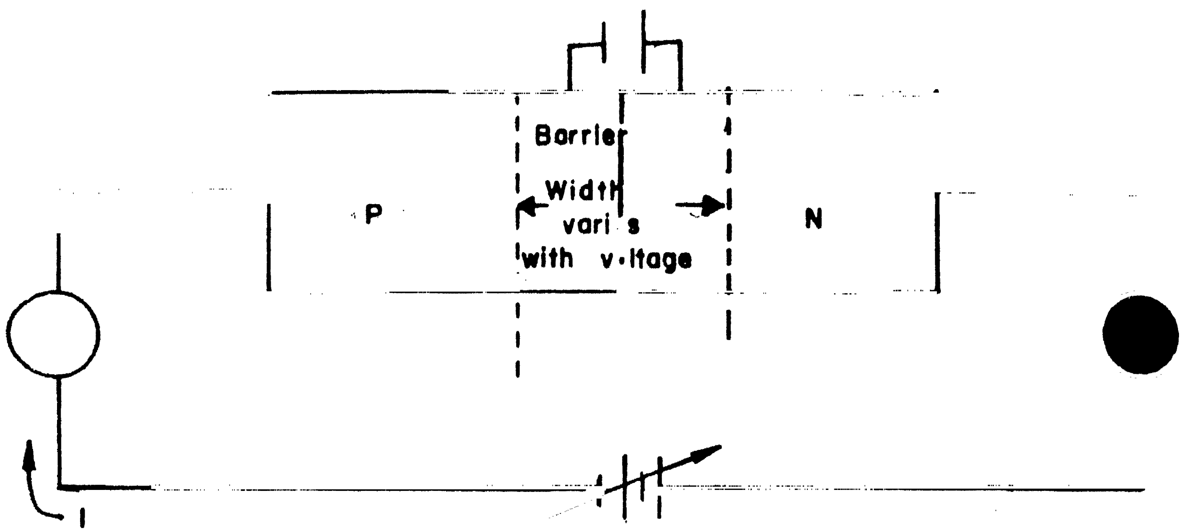
What is happening is that, in reducing the barrier height, the recombination current greatly increases because more holes from the P region and electrons from the N region can cross the junction and recombine. The thermally generated current does not significantly change, for it is solely determined by the temperature and not the voltage. Hence, in the forward bias case, recombination current is much greater than thermally generated (minority) current.

B. We might be tempted to think that putting a volt or two across the junction would annihilate the barrier and permit an enormous current flow. This does not occur because, as the current increases, more and more of the applied voltage is used up as a voltage drop across the bulk of the P and N regions. The barrier can be reduced but not destroyed. Any attempt to reduce the barrier excessively will result in destruction of the semiconductor materials due to the heat dissipated in it.

C. Once the internal barrier potential is greatly reduced by the applied forward bias voltage, the current becomes limited, only by the source resistance of the applied source, the junction lead resistance, and the bulk resistance, and the bulk resistance of the semiconductor materials. The semiconductor material resistance depends on amount of doping, cross-sectional area and length. Such low bulk resistance (about 1 to 200 ohms) can cause excessive current flow; therefore, a current limiting resistor should be placed in series with the semiconductor under forward conditions.

IX. Reverse bias

A. If we reverse the polarity of the external battery, the junction is reverse biased. That is, the negative battery terminal is connected to the P material and the positive battery terminal to the N material as in figure 21.



Reverse bias connection.

Figure 21.

In this case, we see that the field established through the semiconductor by the external battery is such at it tends to aid the internal potential barrier in keeping carriers from crossing to the junction. Mobile holes in the P region are drawn away from the junction toward the negative battery terminal. Mobile electrons in the N region are also drawn away from the junction toward the positive battery terminal. The more reverse bias that is applied, the wider the depletion region grows. If, as is usually the case, the P and N sides are unequally doped, the depletion region will extend further into the region of higher resistivity (material with least doping). This is easy to understand if we visualize the P and N regions are two resistors in series. A larger percentage of the applied voltage will appear across the larger resistor. This effect is important in transistors, for it results in a condition known as <u>punch-through</u>.

B. The reverse bias condition in figure 22 may be explained as follows: At point "A," both bias voltage and current are zero due to recombination current being equal to thermally generated current. As reverse bias is increased, the recombination current is decreased while thermally generated current remains constant. This explains the curved part of the reverse characteristic in the vicinity of the origin (starting down at point "A," figure 22. For greater values of reverse bias, the recombination curruent is negligible, and current essentially equals the thermally generated currents (minority).

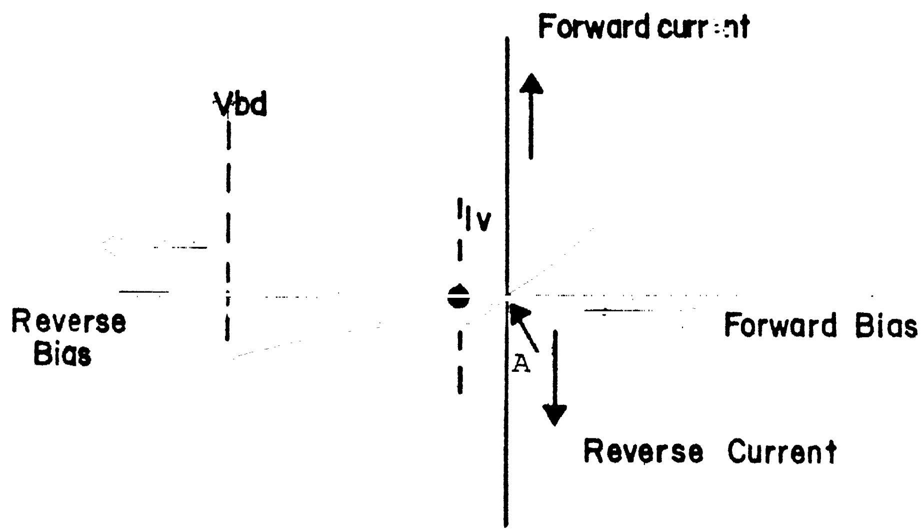


Figure 22.

C. As the reverse voltage is increased, it seems that the reverse current remains constant since it is only temperature and not voltage dependent. However, the curve shows that between -.1 volt and Vbd (voltage breakdown), the reverse current actually increases with reverse voltage. Such a characteristic should be expected if there is some leakage resistance in shunt with the junction. This leakag resistance is due to dirt or other impurities across the junction and little understood surface effects which contribute to leakage resistance.

D. The thermally generated reverse current in the smaller type germanium diodes is usually a few microamps at room temperature (about 25° C). It has been found that minority current for germanium roughly doubles for every 10° C rise in temperature. For silicon diodes, minority currents may be as little a 100 micromicroamps at room temperature because the energy gap in silicon is higher than in germanium and, therefore, at a given temperature, fewer electrons are excited out of covalent bonds into the conduction band. The value of minority current in silicon roughly doubles for every 6° C rise. Even though this is a a more rapid increase than for germanium, the initial value is so low that silicon is generally preferred for high temperature work up to 100 C.

X. Voltage breakdown

A. As the reverse voltage across the junction is gradually increased, a point is reached where the reverse current starts to increase rapidly. This incease may be exceedingly abrupt in silicon junctions. The breakdown characteristic is indicated at Vbd (voltage breakdown) in figure 22. Notice that Vbd stays essentially constant for large variation in current. This is characteristic of a constant voltage source and is the basic principle on which the "voltage-regulating" or zener diodes operate.

B. The sudden increase in current may be the result of either of two mechanisms. First, if reverse bias is sufficiently increased, it is possible for the electrical field in the vicinity of the junction to b ecome quite strong - so strong, in fact, that electrons are suddenly pulled out of covalent bonds when Vbd is reached. This phenomenon is known as <u>zener breakdown</u>.

C. The second and more common type of breakdown, called <u>avalanche breakdown</u>, is due to a secondary emission effect. Minority carriers produced by covalent bond breakup, are accelerated across the junction by the reverse bias. When reverse bias approaches a critical value, the minority carriers have sufficient velocity to knock apart covalent bonds of atoms they collide with, and these in turn break up other bonds, and so forth. The consequence is that a tremendous increase in the number of current carriers results which make the semiconductor material and junction appear to have a low resistance.

D. Diode reverse current in the breakdown region should be limited by an external resistance if reverse bias is to ever equal Vbd. The diode will not be harmed if the current is limited to a value which keeps the power and hence the temperature within safe limits as recommended by the manufacturer.

XI. Junction barrier capacitance

A. The depletion region is an excellent insulator since it is almost free of mobile carriers and in that sense may be likened to the dielectric of a capacitor. The regions bordering the depletion region have good conductivity because of the presence of charge carriers and therefore may be compared to the plates of a capacitor. Since the width of the depletion region is controlled by the magnitude of the reverse voltage, here is a capacitor whose capacitance depends upon the junction voltage. The barrier capacitance varies with the method of fabrication of the junction, but typical values range from 3 to 100 pF.

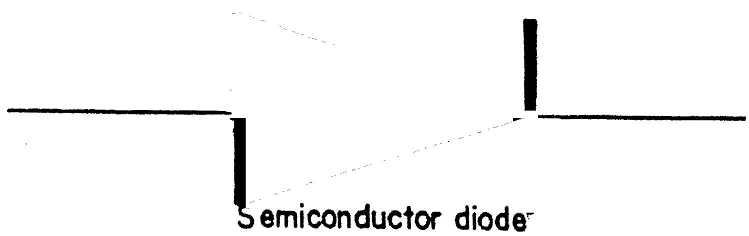
B. In the recent years some manufacturers of semiconductor devices have made voltage-sensitive capacitors commercially available. They have found extensive application in naval electronic equipment, particularly in the field of communications, as oscillator frequency controlling devices.

XII. Diode symbols

A. Some facts hold true of all semiconductor diodes. A few of these are stated here. (Refer to figure 23.)

B. Figure 23 shows schematic representation of a semiconductor diode. The arrowhead of the drawing will always be the anode. The anode will always be the P-type material and the cathode will always be the N-type material.

C. In order to forward bias the diode, the anode must always be positive with respect to the cathode. To reverse bias the diode, the anode must be negative with respect to the cathode.



Semiconductor diode.

Figure 23.

D. When forward biased, the diode will support current flow by means of majority carriers. The circuit current that is supported by majority carriers will always flow against the arrow.

NOTETAKING SHEET 2.4.1N

SEMICONDUCTOR PHYSICS

REFERENCES:

1. Milton S. Kiver. Transistor and Integrated Electronics. New York, NY.: McGraw-Hill Book Company. 1972, Fourth Edition.

2. Slurzberg and Osterheld. Essentials of Radio-Electronics. New York, NY.: McGraw-Hill Book Company, Inc., 1961, Second Edition.

3. Trinklein, Metcalf, Lefler, and Williams. Modern Physics. New York, NY.: Holt, Rinehart, and Winston, Inc., 1968.

NOTETAKING OUTLINE:

I. Atomic structure

A. General information

B. The atom

C. The electrons of an atom

D. Periodic chart

E. Chemical bonding

F. Energy levels of isolated atoms

G. Energy bands

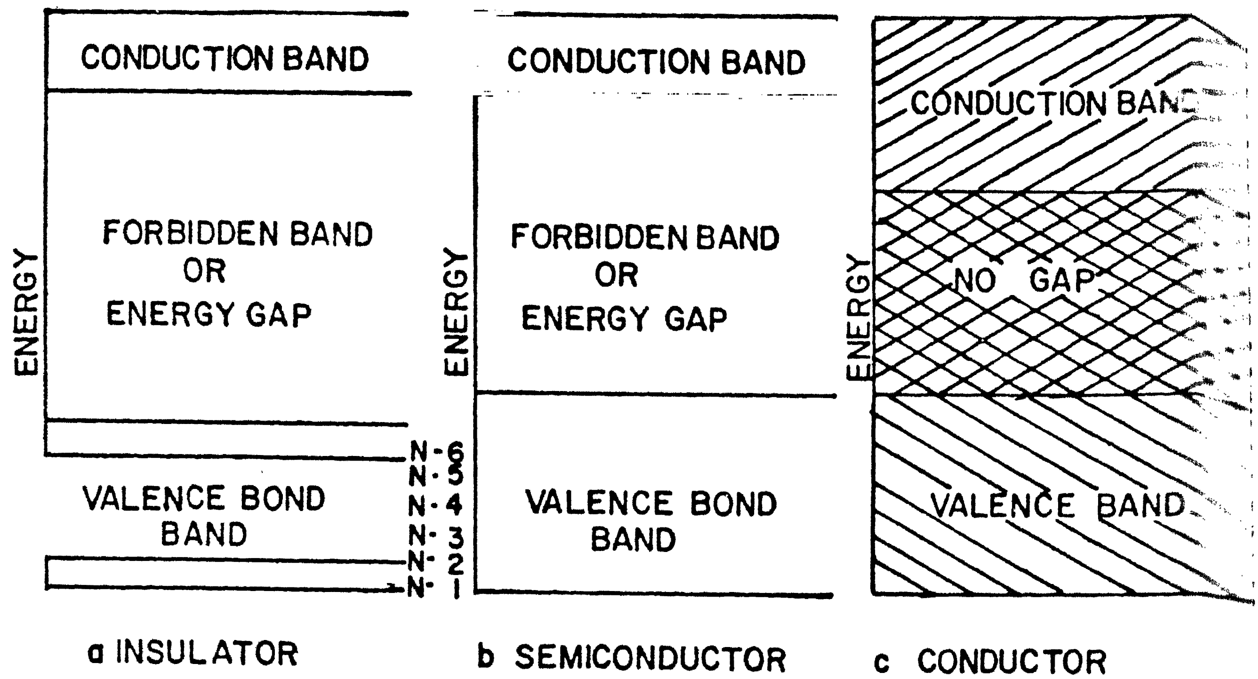


Figure 1. - Energy bands: (a) insualtor (b) semiconductor (c) conductor

II. Intrinsic materials

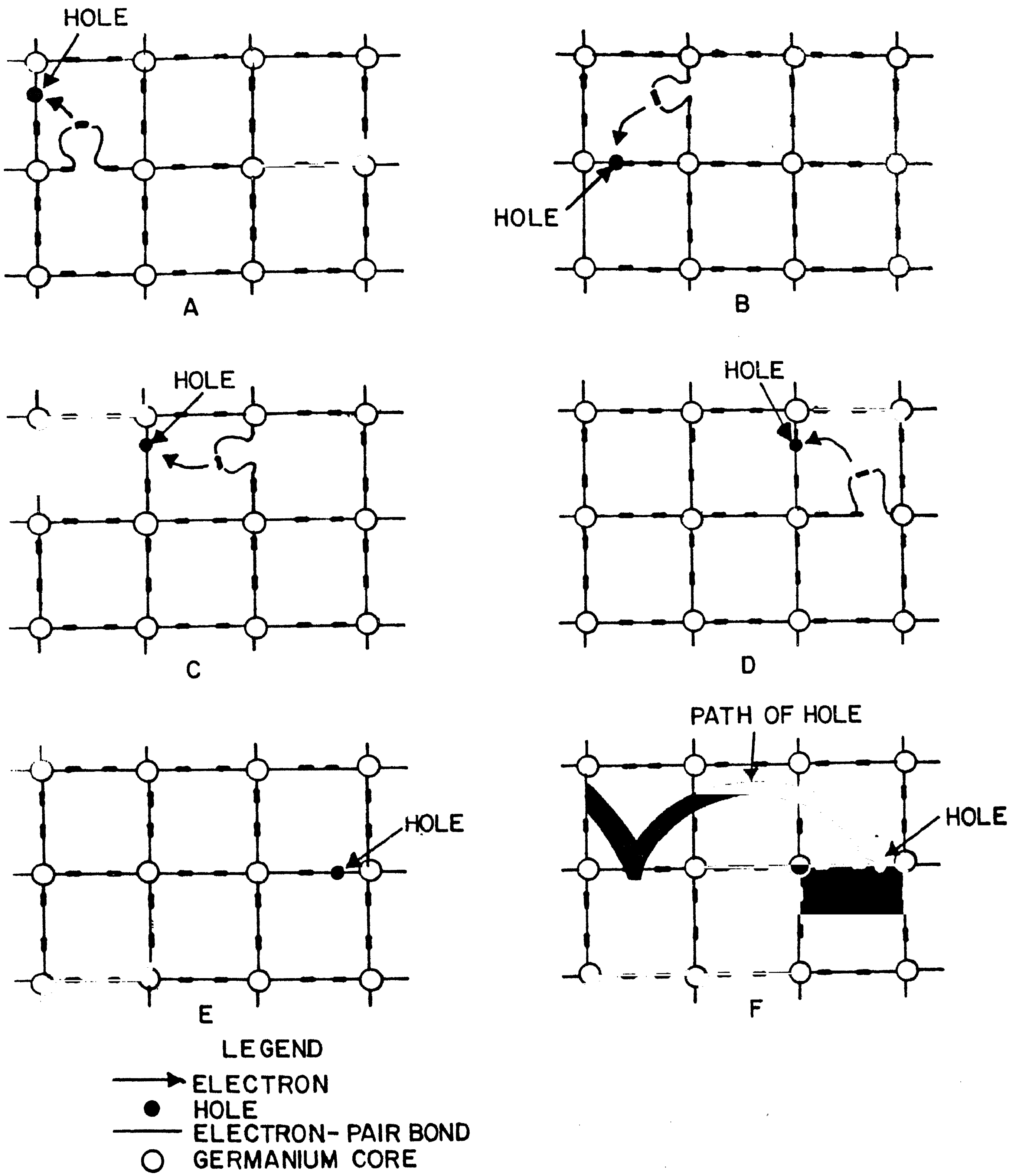


Figure 2.--Movement of hole through crystal.

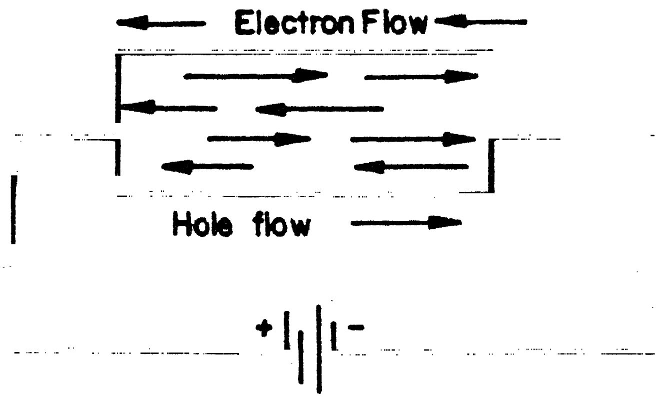


Figure 3.--Intrinsic conduction.

III. Extrinsic materials

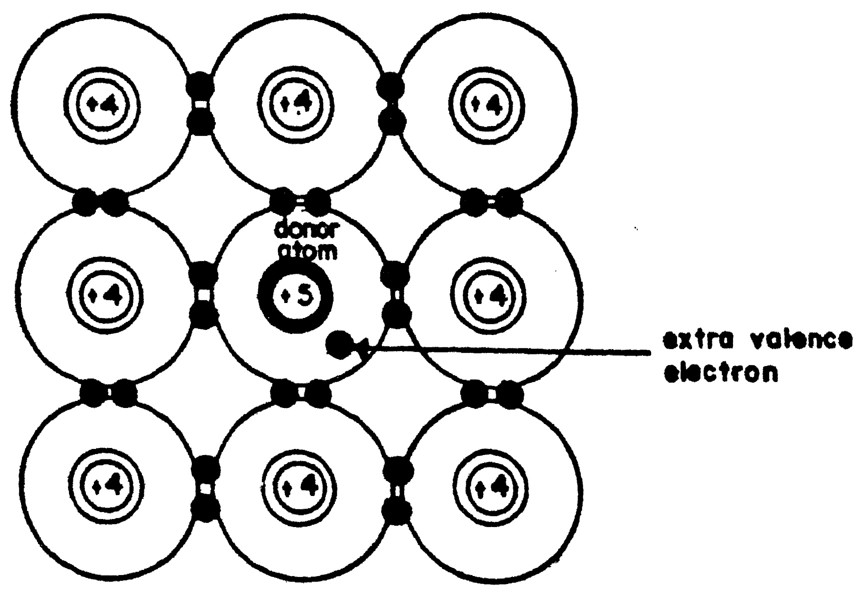


Figure 4.--N-type semiconductor material.

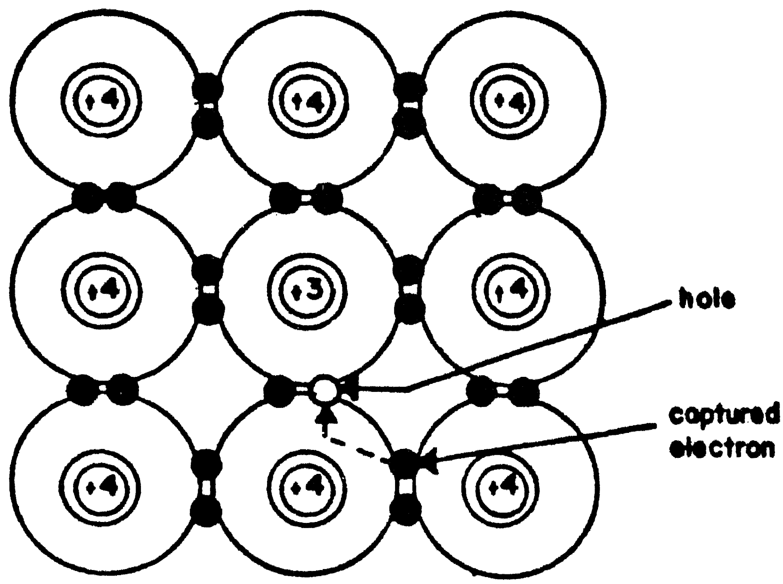


Figure 5.--P-type semiconductor material.

IV. Electrical properties of semiconductors

V. PN junctions

Figure 6.--Diffusion.

VI. Forward biased PN junctions

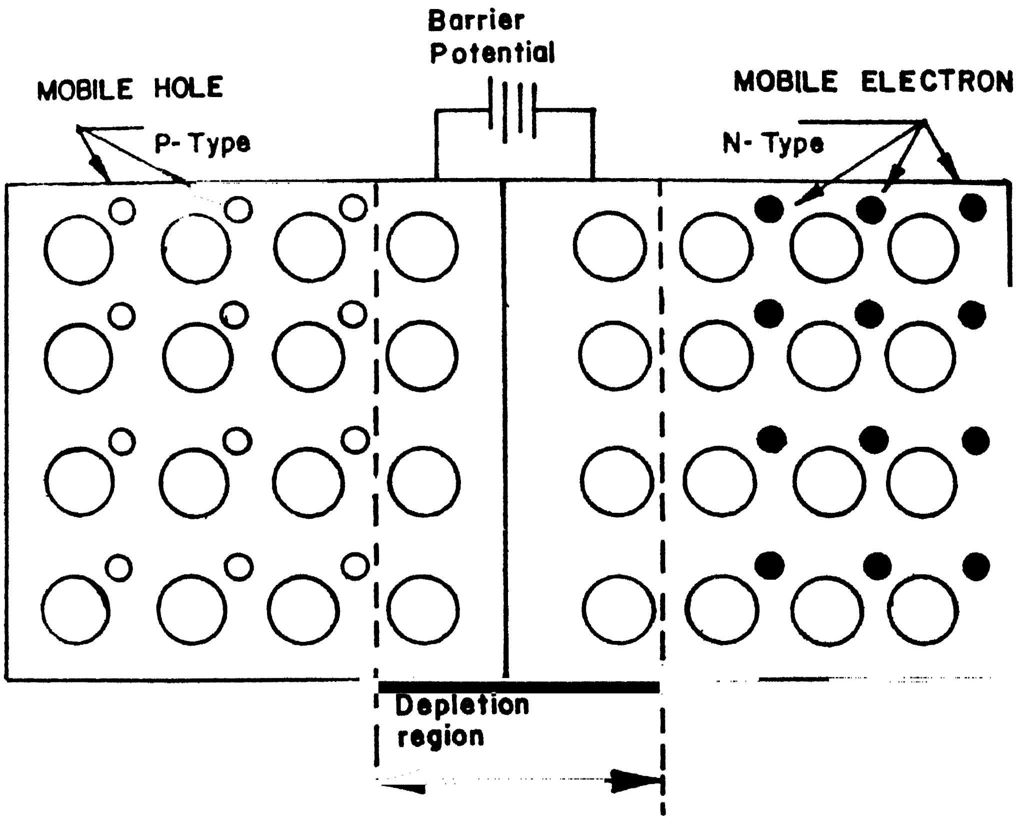


Figure 7.--Charges in an unbiased PN junction.

VII. Reverse biased PN junctions

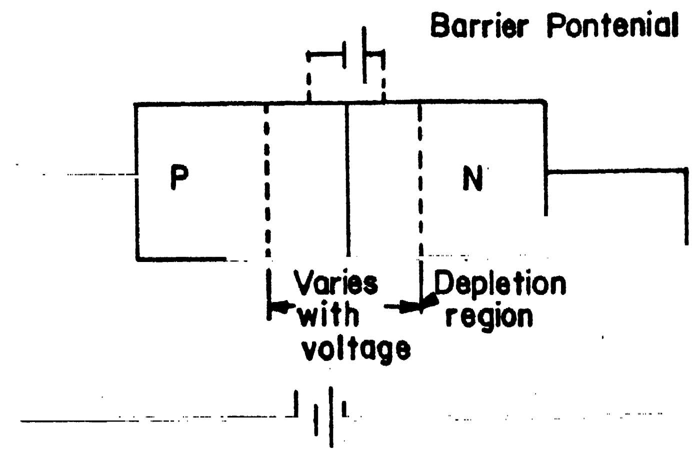


Figure 8.--Forward biased PN junction.

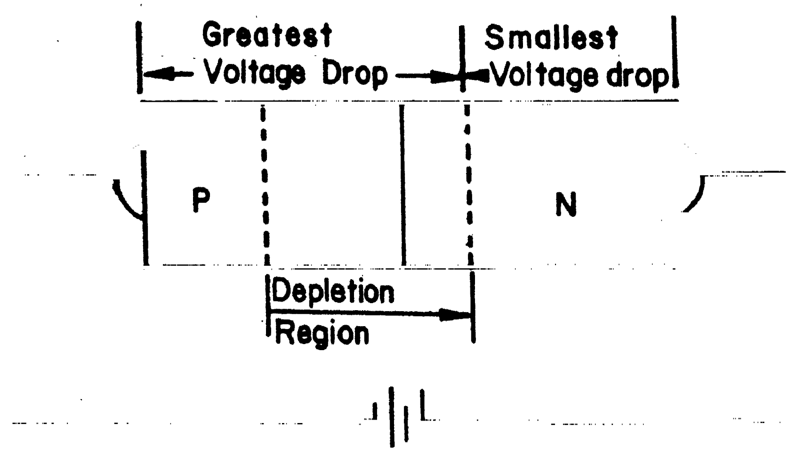


Figure 9.--Reversed bias PN junction.

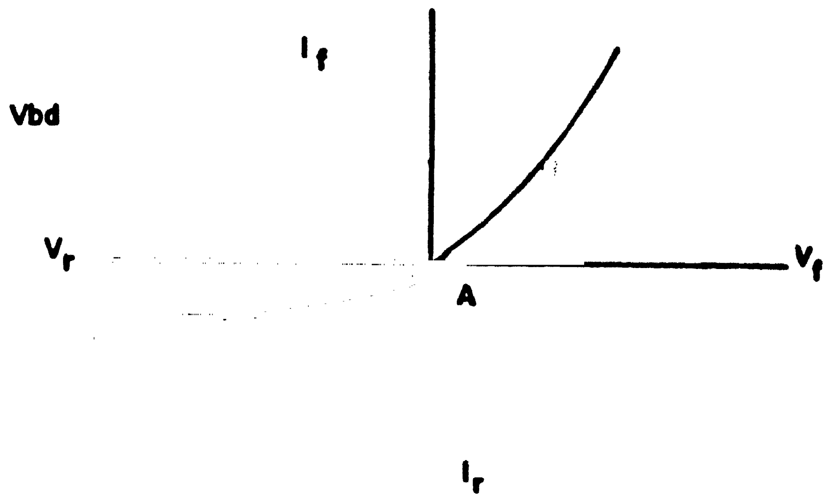


Figure 10.--Reverse bias versus reverse current.

VIII. Diode Symbology and use

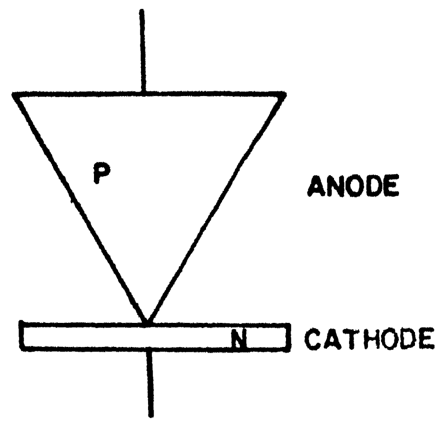


Figure 11. Diode symbology

DATA SHEET 2.5.1D

PN JUNCTIONS LABORATORY

INTRODUCTION

The purpose of the data sheet is for you to record the effects of forward and reverse bias on a PN junction and the effects of temperature changes on current flow through the junction.

1. Forward- and reverse-biased PN junction:

   a. Complete table 1, entering d-c measurements in spaces provided.

FORWARD BIAS		REVERSE BIAS	
$-V_{BE}$	I_B	$+V_{BE}$	I_B
-0.10 V	________	+0.1 V	________
-0.14 V	________	+0.5 V	________
-0.2 V	________	+2.0 V	________

TABLE 1

   b. Complete the following graph, using the information obtained from Table 1.

c. Temperature effects on PN junction

(1) I_B at room temperature ______________

(2) I_B with heat applied ________________

(a) State the effect of heat to the PN junction with respect to minority current carriers. ___________

____

(b) State the effect of removing heat from the PN junction with respect to minority current carriers.

____

d. PN junction resistance calculations:

(1) Forward-bias resistance at -0.2 V ________________

(2) Reverse-bias resistance at +2.0 V ________________

e. Questions (Fill in the blanks.)

(1) The major characteristic of a PN junction when forward biased is ________________ (low/high resistance).

(2) When reversed-biased, the PN junction resistance is very ________ (low/high).

(3) When temperature increases, the amount of reverse current ________________ (increases/decreases).

(4) If not controlled, what effect will a continued increa[se] in temperature have on the PN junction?

____

____

____

Instructor's initials _______

INFORMATION SHEET 2.6.1I

JUNCTION TRANSISTORS

INTRODUCTION

With the increased utilization of transistors, it has become essential that you as technicians acquire an understanding of transistors. The main purpose of this information sheet is to give attention to the fundamental principles of transister action.

REFERENCES

1. Electronic-Circuits, NAVSHIPS 0967-00-0120, pp. 5-10 to 5-20.

2. Essentials of Radio-Electronics, Slurzberg & Osterheld, McGraw-Hill Co., 1961 2nd Editioin.

3. Transistor and Integrated Electronics, Kiver, McGraw-Hill Co., 1972 4th Edition.

I. INFORMATION

A. General information

1. The advantages of using transistors are well known and need only cursory mention. Chief among the advantages are the small physical size and the extreme ruggedness of the transistor. Although designed to perform many of the functions of the vacuum tube, this device requires no filament power and operates with very low bias voltages.

2. Although the disadvantages of the transistor are steadily being diminished, present limitations to its use exist. There is still a basic limitation on the power handling ability, and the temperature dependence of its characteristics are often a challenge. The low resistance of transistors to radiation fields is another disadvantage.

3. With the increased utilization of transistors, it has become essential that technicians acquire an understanding of transistors. The main purpose of this information sheet is to draw forth the fundamental principles of transistor action.

B. Basic transistor action

1. If it were possible to simulate the circuit in figure 1, useful work could be performed.

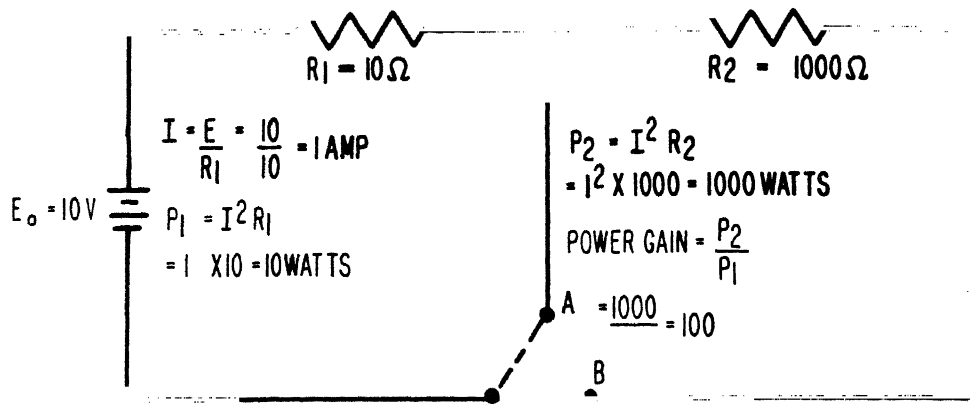


Figure 1 Transfer + Resistor = Transistor

Connecting resistor R_1 in series with the 10-volt batter by placing the switch in position "A" would cause an ampere of current to flow, resulting in a power dissipation in R_1 of 10 watts. If, when throwing the switch to position "B" approximately the same 1 ampere could be made to flow through R_2, a hundredfold gain in power dissipation would result. If R_2 were in a position to offer a large portion of the dissipated power to an external load where useful work could be performed, figure 1 could be considered an active circuit because of its ability to amplify power. The transfer of current across two resistance ratios gives rise to the name transistor, and is the basic analogy of transistor action.

2. It is suggested that the reader review figure 1 and its operation before continuing, and keep in mind throughout the analysis of transistor action that in its simplest form transistor action consists of:

   a. Transferring approximately the same current across unequal resistances.

   b. Utilizing the power developed across the high resistance to perform some useful work.

C. Transistor analysis

1. In your previous lesson on junction diodes, two very important characteristics of biased PN junctions were discussed. Observation of figure 2 reveals that a PN junction biased in the forward direction is equivalent to a low-resistance element (high current for a given voltage).

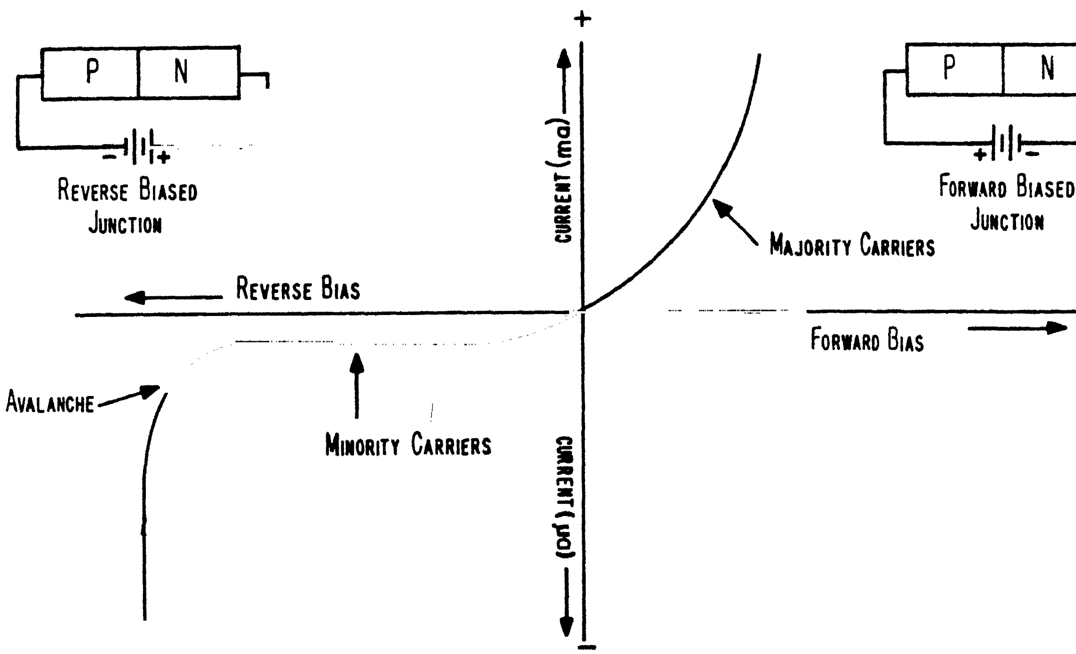


Figure 2: Conditions existing at a forward and reverse-biased PN junction.

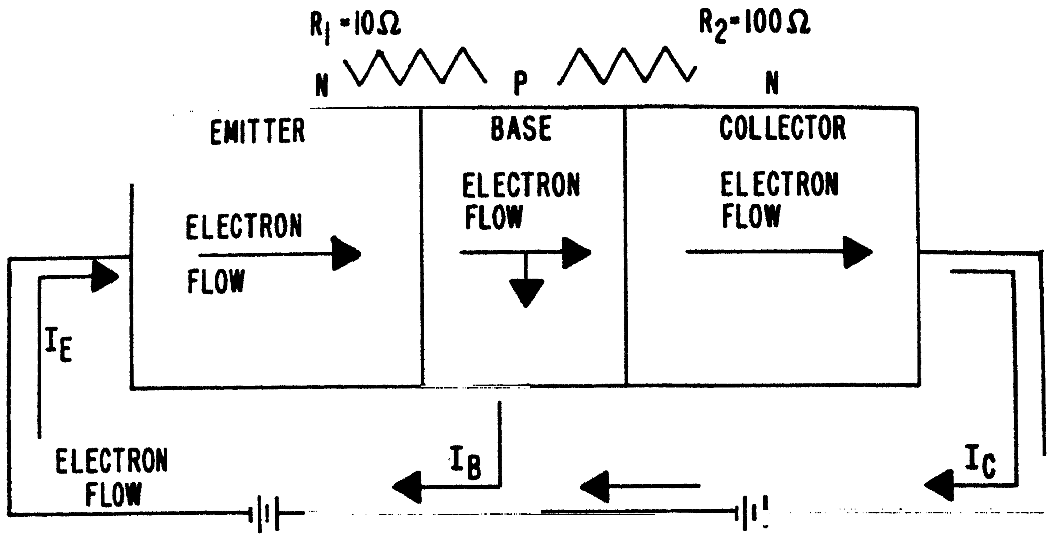
Further observation of figure 2 reveals that the PN junction biased in the reverse direction is equivalent to a high resistance element (low current for a given voltage). Notice also that as the reverse bias voltage increases, the minority current remains relatively contant until avalanche is reached. Thus, it can be seen in figure 2 that:

a. The amount of current flow through a forward-biased junction is primarily voltage dependent.

b. The amount of current flow through a reverse-biased junction is not voltage dependent, but primarily dependent upon the number of minority carriers in the P-and N-type materials.

Applied logic at this time will reveal the transistor action idea.

2. If a crystal containing two PN junctions were prepared, a signal could be introduced into one PN junction biased in the forward direction (low resistance) and extracted from the other PN junction biased in the reverse direction (high resistance). Such a device would transfer the signal current from a low resistance to a high resistance circuit.



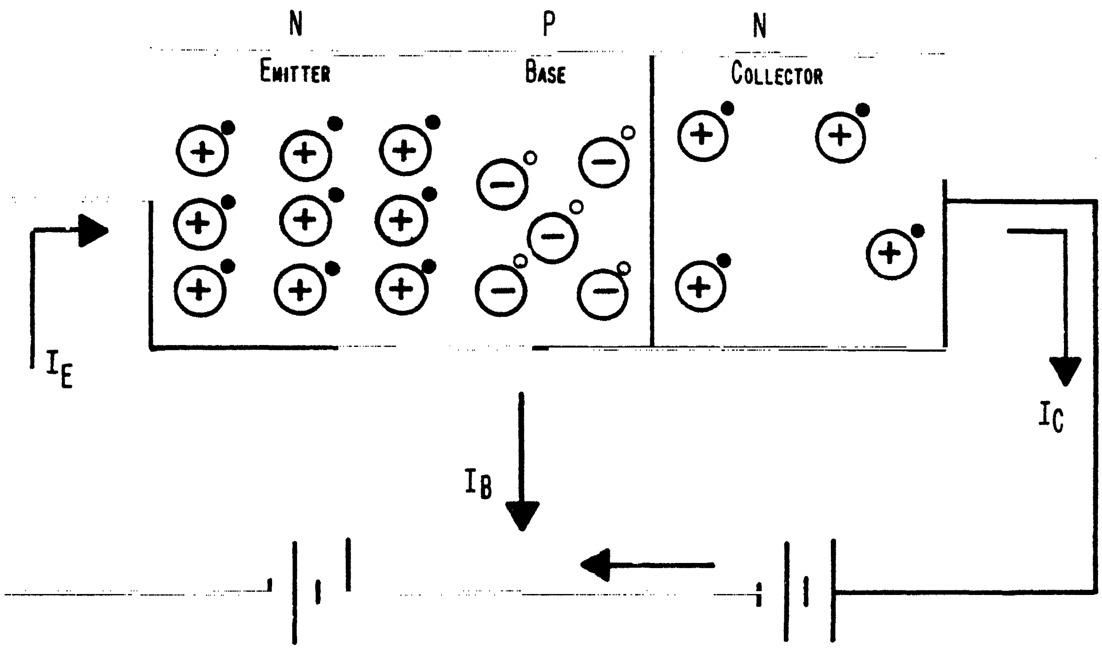
NPN Transistor

Figure 3

3. Figure 3 depicts the basic model of transistor action. Notice that the N-type material labeled emitter is forwa biased with respect to the P-type base, and the N-type collector is reverse biased with respect to the P-type base. Resistors R_1 and R_2 represent the resistance of t emitter-base junction and collector-base junction respectively.

4. A basic analysis is as follows: with the emitter-base junction forward biased a current will flow across the junction. Some of this current will continue on in the P-type base, and some will exit the P-type base to the forward-biased battery. In figure 2, it was pointed out that current flow across a PN junction under reverse-biased conditions is due to minority carriers. In our model, the electrons in the P-type base would be minori carriers. It was also stated that the current across a reverse-biased junction was dependent upon the number o minority carriers and not the bias voltage. Therefore, some percentage of the original carriers (electrons) th crossed the base-emitter junction could cross the collector-base junction. Because the collector-base junction is reverse biased, it offers a high resistance the electrons which cross the junction (represented by resistor R2). Thus, we have transferred current from a low resistance to a high resistance.

5. However, our picture is incomplete at this time. It was also stated earlier that in order to have transistor action, approximately the same amount of current that flowed through the low resistance must also flow through the high resistance. Thus, our problem is to minimize the current flow out of the base lead in figure 3, and to cause most of the current that crosses the emitter-base junction to cross the collector-base junction as well.



+ Fixed Ionized Donor Atom

- Fixed Ionized Acceptor Atom

o Mobile Free Hole

• Mobile Free Electronc

Changes in the Emitter, Base, and Collector Region

Figure 4

6. Figure 4 shows a schematic illustration of the charge distribution in the emitter, base, and collector region of a transistor. The valence 4 atoms; i.e., silicon or germanium, are not shown and should be imagined as a continuous crystal structure over the whole background.

7. Notice that there are more carriers in the N-type emitter than in the P-type base, and that there are more carriers in the base than in the N-type collector (as a result of the manufacturing technique).

8. Considering only the base-emitter junction for the time being, as forward bias is applied to the junction, electrons from the N-type (emitter) material will flow across the junction. On entering the P-type (base) material, they will encounter only a small number of holes and so will travel a long distance before they can recombine. At the same time, holes flowing across the junction from the P-type (base) material will meet a high concentration of electrons and so will very quickly recombine in the N-type region.

9. Re-examination of figure 4 will show that the electrons which enter the P-type base region must travel very deep into the region itself in order to recombine with a hole. The electrons in the base region are in effect trying to spread themselves out in order to recombine. This process was defined in your lesson on PN junctions as <u>diffusion</u>.

10. Each time an electron does recombine with a hole in the P-type base region, the region is no longer electrically neutral, but takes on a negative charge (recall that an atom that takes on an excess electron is defined as a negative ion).

11. In order to regain its electrical balance, the base will give up an electron to the external circuit which gives rise to a current called I_B (base current).

12. Again recall that our goal is to get as much as possible of our emitter current (I_E) to flow through the base region and become collector current (I_C). (Again review figure 1.) Figure 3 reveals that collector current (I_C) is simply the emitter current (I_E) minus any base current (I_B).

$$I_C = I_E - I_B$$

Therefore, minimizing I_B will cause I_C to approach I_E.

13. The action taken to minimize I_B should be very easily understood at this time. As stated earlier, the electrons must travel by diffusion through the base region. The distance they travel through the P-type (base) region before they recombine with a hole is called their diffusion length. Now, let us introduce another PN junction by arranging a second N-type material (collector) to the right of the base and, at the same time, make the base itself very thin. As the electrons diffuse through the center P-type (base) region, some of them recombine in the process. However, if the width of the base is made very small as compared to the diffusion length of the electrons only a few recombinations will have taken place within the base region before the main flow reaches the second PN junction (collector-base).

14. Note that the collector-base junction is reverse biased to the majority carriers in the collector and base; i.e., electrons in the N-type collector and holes in the P-type base. But the carriers diffusing toward the collector-collector-base junction are electrons in the P-type base material (minority carriers). Therefore, the collector-base junction will appear as a forward bias, and the electrons will be swept across the junction. These excess electrons in the N-type collector will give it an excess negative charge which it can easily give up to the external battery terminal in the form of I_C. Recall also that it is not the reverse bias voltage that is controlling the amount of electrons, but the forward biased emitter-base junction which controlled the electrons flowing into the base.

5. The process of causing majority carriers to cross over a PN junction and flow as minority carriers on the other side is called injection. This process describes precisely the action that takes place at the emitter-base junction.

6. Our picture on transistor action is now complete, and can be described as three basic mechanisms:

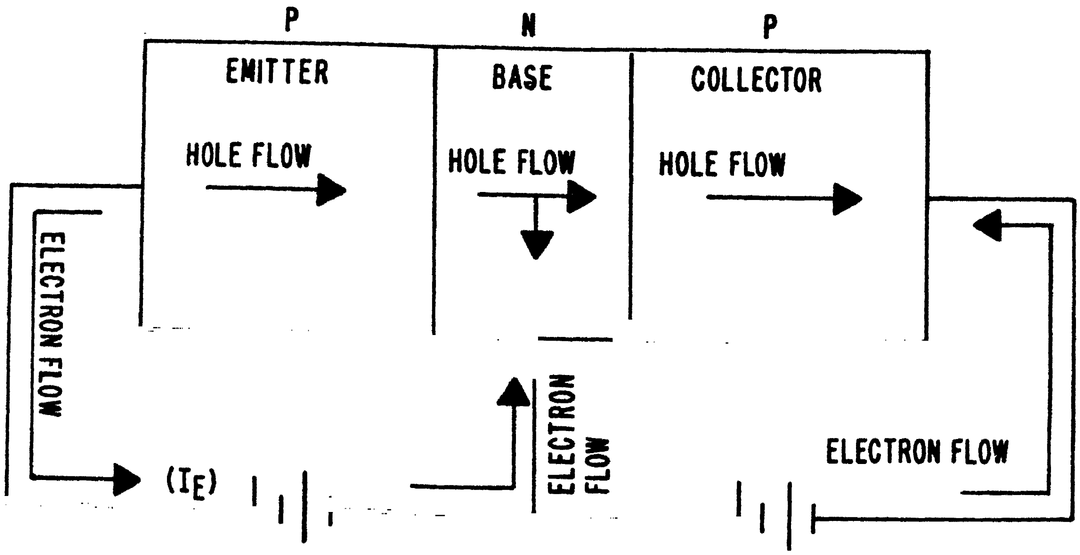
   a. Injection - The process (under forwrd bias conditions) where majority carriers from the emitter are made to cross the emitter-base junction and flow as minority carriers in the base region.

   b. Diffusion - The process by which the minority carriers (electrons) in the P-type base region travel (from an area of high carrier concentration to an area of low carrier concentration).

   c. Collection - The process of causing minority carriers (electrons in a P-type material) to become majority carriers (electrons in an N-type material) and giving them up to the external circuit.

7. In our transistor model, external current was supported by majority carriers (electrons) in the transistor itself. The electrons are majority carriers in both the emitter and collector, both of which are N-type carriers. The same three mechanisms of transistor action can be achieved in a PNP transistor.

8. Figure 5 depicts the basic model of a PNP transistor. Notice that in this configuration the emitter and the collector are both P-type material, and the base is N-type material. The emitter-base junction is forward biased, and the collector-base junction is reverse biased. However, note that in order to achieve the correct bias polarities, the batteries are connected opposite to those shown in figure 3 (NPN transistor).



PNP Transistor

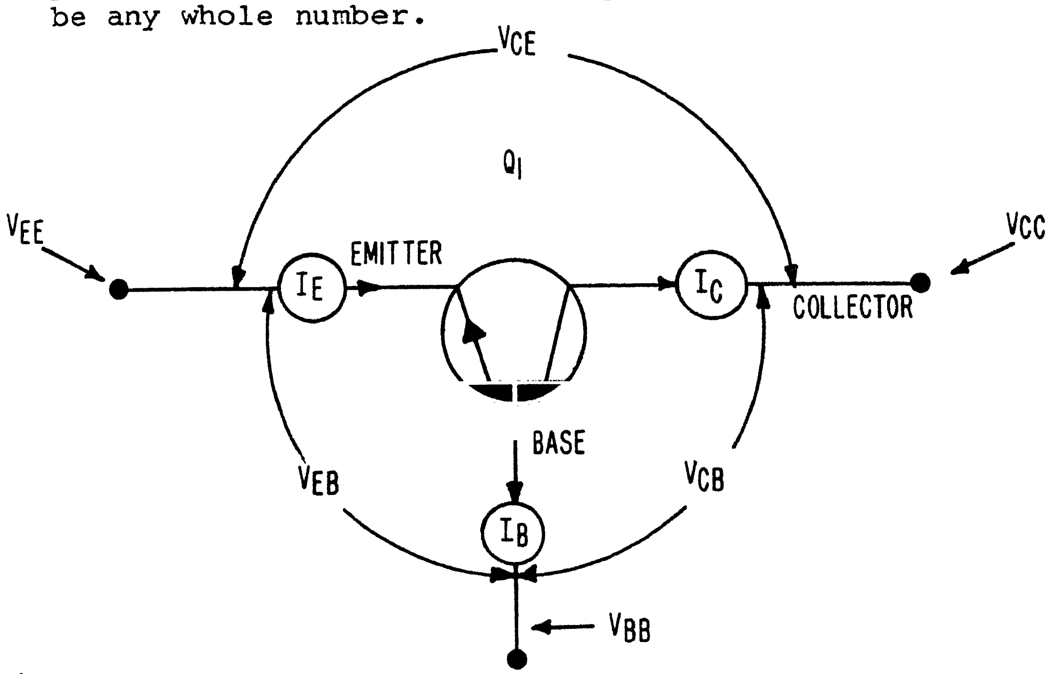
Figure 5

19. As forward bias is applied to the emitter-base junction, holes are accelerated across the emitter-base junction. Once the holes enter the base region, they become minority carriers (holes in an N-type material). The holes will recombine with some of the excess electrons in the N-type base, creating positive ions. In order to regain its electrical balance, the base will readily accept an electron from the external circuit for each positive ion which is created by an electron-hole recombination. However, in order to reduce the number of recombinations in the base, the base is made very thin and the emitter more heavily doped just as in the case of the NPN transistor (figure 4). The holes that do not recombine in the base region continue to travel by the diffusion process; i.e., from an area of high carrier concentration to an area of lower carrier concentration. Those holes which diffuse near the reverse-biased collector-base junction are swept across the junction by the reverse bias electric field. Once these holes enter the P-type collector region, the collector must accept electrons from the external circuit in order to achieve its electrical balance.

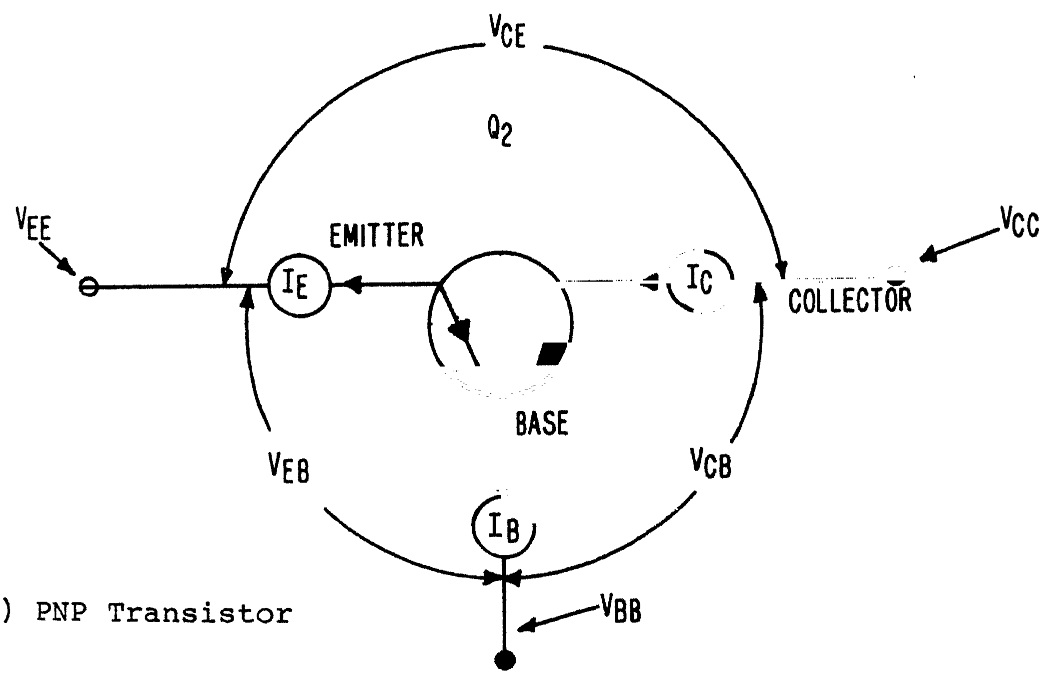
20. Thus, the external circuit current (electrons) is supported by internal majority current carriers. In the PNP transistor majority carriers are holes in the emitter and collector P-type material.

D. Transistor schematic symbology

1. The reference designations and schematic symbols for transistors are shown in figure 6 (A) and (B). The letter portion of the reference designation is Q. The number may be any whole number.



(A) NPN Transistor



(b) PNP Transistor

Figure 6 Transistor Schematic Symbols

In the NPN transistor (A, figure 6), the emitter-to-collector current carrier in the device is the electron. For electrons to flow internally from emitter to collector, the collector must be positive with respect t the emitter. In the external circuits, electrons flow from the emitter to the collector or opposite to the direction of the emitter arrow.

2. In the PNP transistor (B, figure 6), the emitter-to-to-collector current carrier in the device is the hole. For holes to flow internally from emitter to collector, the collector must be negative with respect to the emitter. In the external circuit, electrons flow from t collector to emitter opposite to the direction of the emitter arrow.

3. The following generalizations are helpful in analyzing t behavior of transistor circuitry. These generalizations apply to a transistor that is operated as a class A amplifier.

   a. The first letter of the type of transistor indicates the polarity of the emitter voltage with respect to the base. A PNP transistor has positive d-c voltage applied to the emitter ($+V_{EE}$). A NPN transistor has negative voltage applied to the emitter. ($-V_{EE}$).

   b. The second letter of the type of transistor indicate the polarity of the collector with respect to the base. A PNP transistor has negative d-c voltage applied to the collector ($-V_{CC}$). An NPN transistor has positive d-c voltage applied to the collector ($+V_{CC}$).

   c. The first and second letter of the type transistor indicate the relative polarities between the emitter and the collector respectively. In a PNP transistor the emitter is positive with respect to the collectc the collector is negative with respect to the emitte ($-V_{CE}$). In an NPN transistor, the emitter is negati with respect to the collector; the collector is positive with respect to the emitter ($+V_{CE}$).

   d. The d-c electron current direction is always against the direction of the arrow on the emitter (I_E).

   e. If the electrons flow into or out of the emitter, th electrons flow out of or into the collector respectively (I_C).

   f. The base current is always equal to the emitter current minus the collector current ($I_B = I_E - I_C$).

g. The base-emitter junction is normally forward biased. In a PNP transistor, the base is negative with respect to the emitter ($-V_{BE}$). In an NPN transistor, the base is positive with respect to the emitter ($+V_{BE}$).

h. The collector-base junction is normally reverse biased. In a PNP transistor, the collector is negative with respect to the base ($-V_{CB}$). In an NPN transistor, the collector is positive with respect to the base ($+V_{CB}$).

i. An input voltage that aids (increases) the forward bias increases the emitter and collector currents.

j. An input voltage that opposes (decreases) the forward bias decreases the emitter and collector currents.

k. The reverse bias voltage (V_{CB}) is normally much greater than the forward bias voltage (V_{BE}) in a transistor. Typical values of V_{CB} range from 3 to 8 volts d-c. Typical values of V_{BE} are .2 volts d-c for germanium and .6 volts d-c for silicon crystals.

II. Circuit Configurations

A. Since the transistor is a three-element, three lead device, it is possible to use it in any of three different, useful configurations. The identification of each of these individual circuits is derived from the element "common" to both input and output. The three possible connections are: common-base, common-emitter, and common-collector. An often used variation is "grounded' emitter, "grounded" base, etc., since the common element is usually returned to the signal ground point in a circuit.

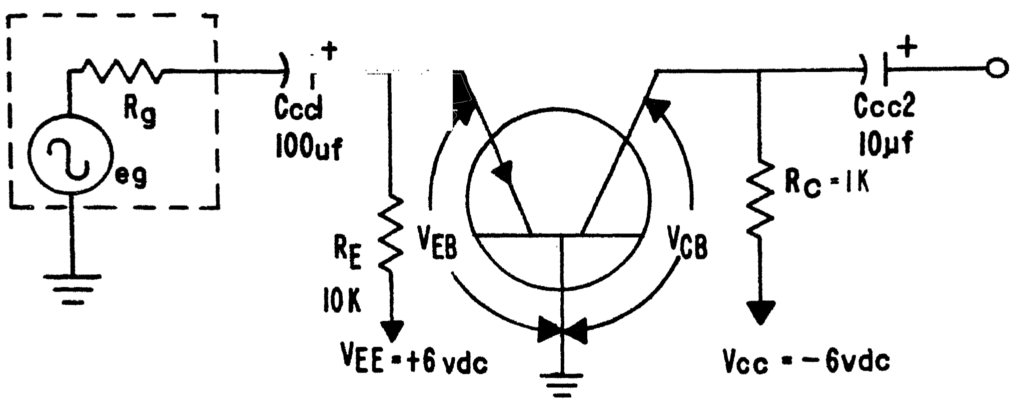
B. Common-base amplifier

1. It is convenient to start a detailed examination with the common-base amplifier, which is normally considered to be the "reference amplifier" for any comparisons of the three amplifier configurations.

2. Figure 7 is a schematic drawing of a common-base amplifier of the PNP type. Notice that the input is supplied between the emitter and base. Thus, the base is common to both the input and output. In "transistor symbology" you were given some general rules to follow when analyzing transistor circuits. Following these rules, you will find for proper operation that V_{EE} must be a positive voltage and V_{CC} a negative voltage for proper bias potentials.

3. The input signal is coupled to the emitter. The emitter bias is established by +6 volts (V_{EE}). Current flow through the emitter is limited by R_E, a 10 k-ohm resistor The resultant I_E (approximately equal to $\frac{V_{EE}}{R_E}$ will develop a small forward bias voltage across the emitter-base junction (V_{EB}). The forward bias voltage will be very small (.2 to .6 volts). V_{CC} is the collector supply source, and R_C is chosen to provide the desired voltage gain. The reverse-bias voltage (V_{CB}) is equal to V_{CC} - $I_C R_C$. The reverse bias voltage will normally be very larg (3 to 6 volts) as comapred to the forward bias voltage.

4. Let us analyze the amplifier under dynamic (signal) conditions.



Common-Base Amplifier

Figure 7

5. As the incoming signal goes negative, it will counteract some of the normal positive bias between emitter and base (V_{EB}). As stated earlier, an input voltage that opposes (decreases) the forward bias will decrease the emitter and collector currents. The decreasing collector current will reduce the voltage drop across R_C, making the collector potential more negative. ($V_{CB} = V_{CC} - I_C R_C$). Thus, a negative-going input signal produces a negative-going output signal. During the positive half-cycle of the input signal, the emitter will be driven more positive than it was under static (no signal) conditions. This will increase the current in the emitter and collector leads and cause the voltage drop across R_C to increase. Again, we see that the polarity of the input signal determines the polarity of the output signal.

6. For the output, a load resistor (R_C of 1000 ohms) is used. Insofar as the current is concerned, there is less at the output (i.e., collector) than at the emitter. $I_C = I_E - I_B$. The difference (I_B) is normally 1 or 2 percent of the total current in the device (I_E).

7. The ratio of the change in the output current (I_C) to the change in the input current (I_E), or $\frac{I_C}{I_E}$, is referred to as the "alpha" (∂) of the transistor. Thus, the current gain of this amplifier arrangement is less than 1, and this might lead one to believe that the circuit has little use. This is not true; a large voltage gain may be obtained because the output load resistance is much greater than the input resistance. Thus, if we assume an input resistance of 50 ohms (the forward biased emitter-base junction) and utilize a 1000 ohm load resistance, the voltage gain (input to output) is:

$$\text{Voltage gain} = \frac{\Delta E_{out}}{\Delta E_{in}} = \frac{\Delta I_C R_C}{\Delta I_E R_{in}}$$

$$= \frac{\Delta I_C}{\Delta I_E} = 0.98 \text{ for a typical value}$$

Hence,

$$\text{Voltage gain} = \frac{\Delta E_{out}}{\Delta E_{in}} = 0.98 \times \frac{1000}{50}$$

$$= 0.98 \times 200$$

$$\text{Voltage gain} = 19.6$$

By the same token, a power gain is also possible:

$$\text{Power} = I^2R$$

$$\text{Power gain} = \frac{\Delta P_{out}}{\Delta P_{in}}$$

$$= \frac{\Delta I_C{}^2 R_C}{\Delta I_e{}^2 R_{in}}$$

$$= .98^2 \times 20$$

$$= .96 \times 20$$

$$\text{Power gain} = 19.2$$

8. In the input impedance of a transistor in the common-base configuration is very low because of the forward biased emitter-base junction. The output impedance, if we remove the load resistor and look into the collector, is very high, on the order of 1 to 2 megohms. However, when we connect a load resistor of 1000 ohms, then this is the value of the output impedance since it completely swamps the 1 to 2 megohms with which it is basically in parallel. It is well for the reader to keep this distinction in mind, because reference is often made in literature to the high output impedance of the common-base arrangement, and this means without the load resistor. Once a much smaller load resistance is connected to the collector, its value will essentially determine the output impedance.

9. In summary, the characteristics of the common-base amplifier configuration are:

   a. No phase inversion between input and output.

   b. Low input resistance because of forward biased junction (V_{EB}) typical values 50-100 ohms.

   c. The output signal sees a reverse biased junction (V_{CB}).

      (1) Typical values 1-2 megohms.

      (2) In a practical circuit, R_C shunts the output resistance of the transistor.

   d. The output to input resistance ratio is high. This leads to a very high voltage gain.

e. The current gain is less than 1.

$$\frac{\text{Output}}{\text{Input}} = \frac{\Delta I_C}{\Delta I_E} = \alpha$$

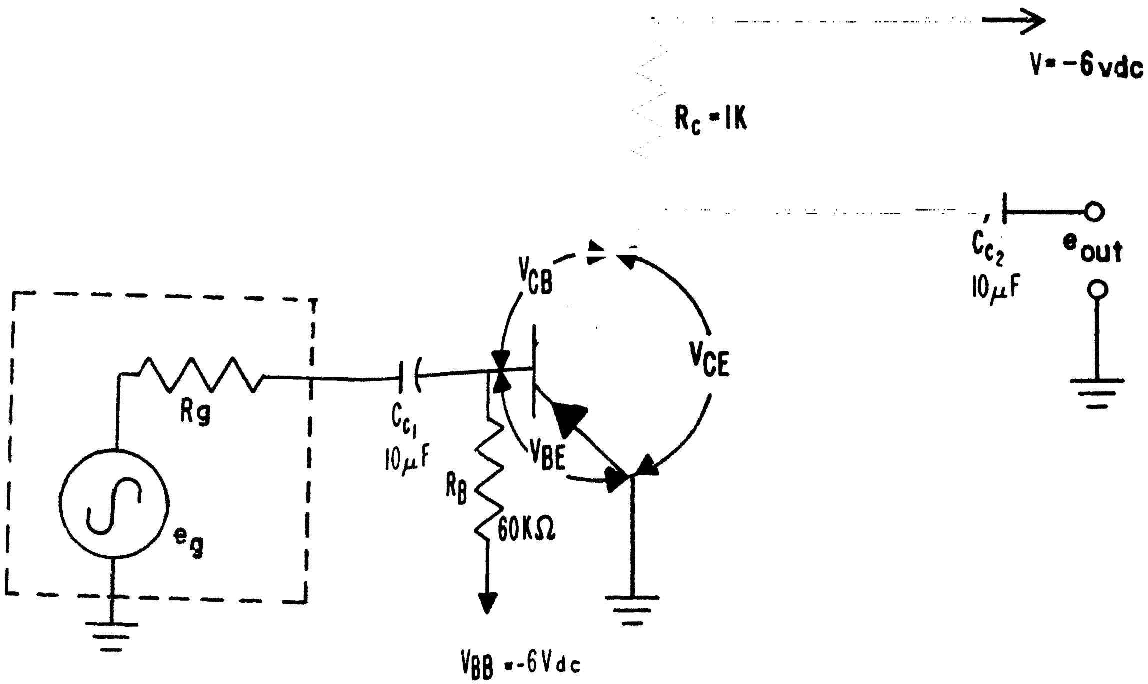
f. The power gain is moderate. Low current gain times a high voltage gain.

g. The input signal is applied between the emitter and the base.

h. The output signal is taken between the collector and the base.

i. The base is "common" to both the input and the output.

C. Common-Emitter amplifier



Common-Emitter Amplifier

Figure 8

1. The common-emitter amplifier shown in figure 8 is the most popular amplifier configuration of the three types, for reasons that will become quite obvious. Notice the polarities of the bias supplies V_{BB} and V_{CC}. These voltage polarities are necessary for proper operation as outlined previously under "transistor symbology." The input signal is coupled to the base. The base bias is established by -6 volts (V_{BB}). Current flow through the base is limited by the base resistor R_B, a 60 k-ohm resistor. The resultant I_B (approximately equal to $\frac{V_{BB}}{R_B}$) will develop a small forward bias voltage across the base emitter junction (V_{BE}).

2. As is normally the case, this forward bias voltage will be very small. V_{CC} is the collector supply source, and R_C is chosen to provide the desired voltage gain. The reverse bias voltage (V_{CB}) is equal to $V_{CC} - I_C R_C - V_{BE}$.

3. Again, let us analyze the amplifier under dynamic conditions. As the incoming signal goes negative, it will aid (increase) the normal negative bias between base and emitter (V_{BE}). An input voltage that aids the forward bias will increase the emitter and collector currents. The increasing collector current will increase the voltage drop across R_C, making the collector potential (V_C) more positive ($V_C = V_{CC} - I_C R_C$). Thus, a negative-going input signal produces a positive-going output signal. During the positive half-cycle of the input signal, the base will be driven more positive than it was under static (no signal) conditions. This will decrease the current flow in the emitter and collector leads causing the voltage drop across R_C to decrease. This decreased voltage drop will cause V_C to become more negative. Thus, in the common-emitter amplifier polarity inversion between input and output.

4. For the output, a load resistor of 1000 ohms will again be utilized to compare the characteristics of the amplifier to those of the common-base amplifier.

5. Since the input signal is applied to the base in the common-emitter amplifier, it is the variations in the signals on the base which control the collector current. As stated previously, $I_C = I_E - I_B$. It was also stated that the difference in I_E and I_C is I_B, which is normally 1 or 2 percent of the total current (I_E). In fact, the transistor was intentionally designed to minimize I_B; i.e., thin base region, heavily doped emitter. Thus, it follows that very minute variations of base current produce significant variations in collector current. If we assume base current

to be 2% of total current (I_E), and the base current were .1 mA ($\frac{V_{BB}}{R_B}$), the emitter current would be 5 mA and the collector current 4.9 mA. ($I_C = I_C - I_B$).

Hence, the current gain in the common-emitter amplifier is

$$\text{Current gain} = \frac{\Delta I_C}{\Delta I_B}$$

The ratio of $\frac{\Delta I_C}{\Delta I_B}$ is called Beta (β). In our amplifier the base current would be .1 mA, while the collector received 4.9 mA. Substituting these values, we obtain

$$\beta = \frac{\Delta I_C}{\Delta I_B}$$

$$= \frac{4.9 \text{ ma}}{.1 \text{ ma}}$$

$$\beta = 49$$

6. Note that a sizeable current gain is obtained, in contrast to the small loss incurred in the common-base amplifier. The input resistance of the common-emitter amplifier is quite a bit higher than the input resistance of the common-base amplifier. As was the case with the common-base amplifier, the input is applied across a forward-biased junction (V_{EE}); however, the current flow through the junction (I_B) is quite small as compared to the current flow through the common-base forward-biased junction.

$$R_{in} = \frac{\Delta V_{BE}}{\Delta I_B}$$

$$\text{Typical values} = \frac{.2 \text{ volts}}{.1 \text{ mA}} = 2 \text{ k-ohms}$$

The output impedance, looking into the collector, before any load is connected, is about 500,000 ohms. This is somewhat less than the value presented by the common-base amplifier. As was the case in the common-base amplifier, the 1000 ohm load resistor R_C will swamp out the 500,000 ohm output impedance.

7. Thus, a voltage gain will also be obtained because of the current gain and the resistance ratio of the common emitter amplifier configuration.

Voltage gain = current gain x resistance

$$= \frac{\Delta I_C}{\Delta I_B} \times \frac{R_L}{R_{in}}$$

$$= 49 \times \frac{1000}{2000}$$

$$= 24.5$$

8. This is somewhat larger than the voltage gain achieved with the common-base amplifier. The difference is not very much; however, power gain is considerably better.

$$\text{Power gain} = \frac{\Delta I_C{}^2 R_L}{\Delta I_B{}^2 R_{in}}$$

$$= 49^2 \times .5$$

$$= 1200.5$$

9. In summary, the characteristics of the common-emitter amplifier are:

   a. There is a polarity inversion between the input and output.

   b. Higher input resistance than the CB amplifier. Typical value 2 k-ohms.

   c. The output resistance of the common-emitter is slightly less than that of the common-base amplifier. However, R_C will shunt the output just as it did the common-base amplifier.

   d. The output to input resistance ratio is moderate. This leads to a good voltage gain.

   e. There is a good current gain in the common-emitter configuration.

$$\frac{\Delta I_C}{\Delta I_B} = \beta$$

(1) To relate β to α

(a) $\beta = \dfrac{\Delta I_C}{\Delta I_B}$

(b) $I_B = I_E - I_C$

(c) $\beta = \dfrac{I_C}{I_E - I_C}$

(2) Dividing denominator and numerator by I_E

$$\frac{\frac{I_C}{I_E}}{\frac{I_E}{I_E} - \frac{I_C}{I_E}}$$

(3) However, $\dfrac{\Delta I_C}{\Delta I_E} = \alpha$

f. By substitution; $\beta = \dfrac{\alpha}{1 - \alpha}$

(1) It can be seen that by keeping the recombination currents in the base circuit very low, alpha approaches unity.

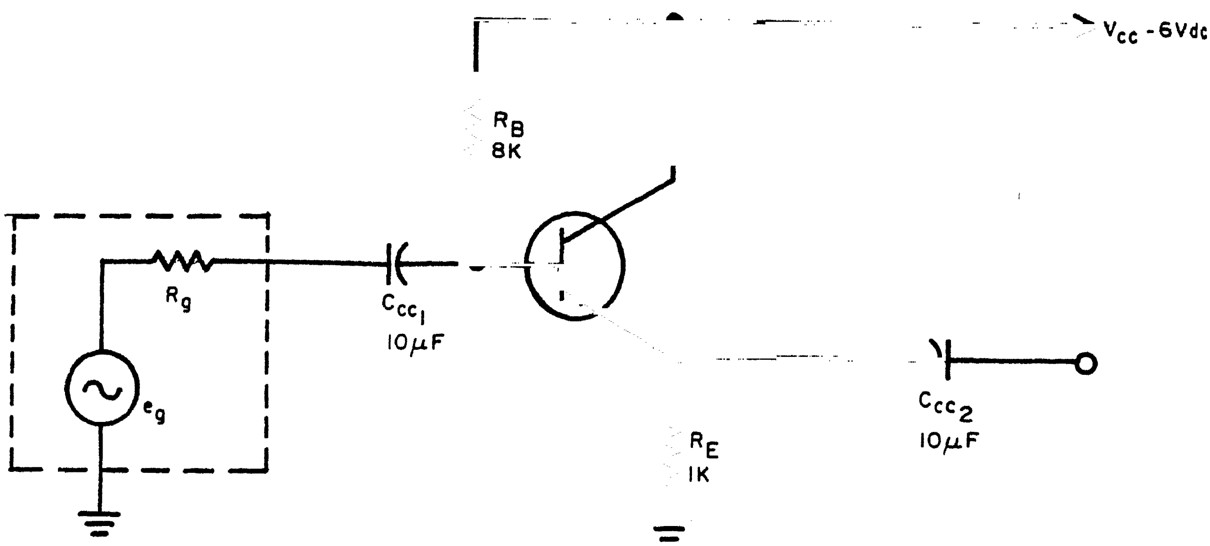
(2) As α approaches unity, β will approach infinity.

g. There is a very high power gain in the common-emitter amplifier.

10. It is because of its higher current gains, power gains, and the relatively close input-to-output impedance ratio (1 to 2 in our example), that the common-emitter amplifier configuration is the most popular configuration in transistor circuits.

D. Common-Collector Amplifier

1. The final transistor amplifier circuit arrangement is the common-collector. This is shown schematically in figure 9. Note that the collector of the transistor is not at d-c ground since the collector still requires a $-V_{CC}$. Note also the bias polarities. They are the same polarities as were required for the common-emitter amplifier in figure 8.



Common-Collector Amplifier

Figure 9

2. The input signal will be developed across the base-collector junction (the collector is the common element), and the output signal will be developed across the emitter resistor R_E. Thus, in the common-collector amplifier, the input is applied to the base and the output is taken from the emitter with the collector the common element.

3. Analyzing the amplifier under dynamic conditions, as the incoming signal goes negative, it will aid the normal negative bias between base and emitter (V_{BE}). An input that aids forward bias will increase the emitter and collector currents.

4. The increasing emitter current will increase the voltage drop across the emitter resistor R_E (negative to positive from the top of R_E). Therefore, a negative-going input signal will develop a negative-going output signal. During the positive half-cycle of the input signal, the base will be driven more positive than it was with no signal applied. This will decrease forward bias, and will lend to a decreasing current in the collector and emitter leads. The decreased emitter current will decrease the voltage drop across the emitter resistor, causing the output signal to go in the positive direction, Thus, in the common-collector configuration, there is no polarity inversion between input and output. The current gain of a common-collector amplifier is slightly higher than was the current gain (β) in the common-emitter amplifier.

5. The reason for this is fairly simple and can be shown as follows: the input current is the base current, I_B. The output current is the emitter current I_E, and this we know is equal to $I_B + I_C$. Hence,

$$\text{Current gain} = \frac{\Delta I_E}{\Delta I_B} = \frac{I_C + I_B}{I_B}$$

$$= \frac{I_C}{I_B} + \frac{I_B}{I_B}$$

$$= \beta + 1$$

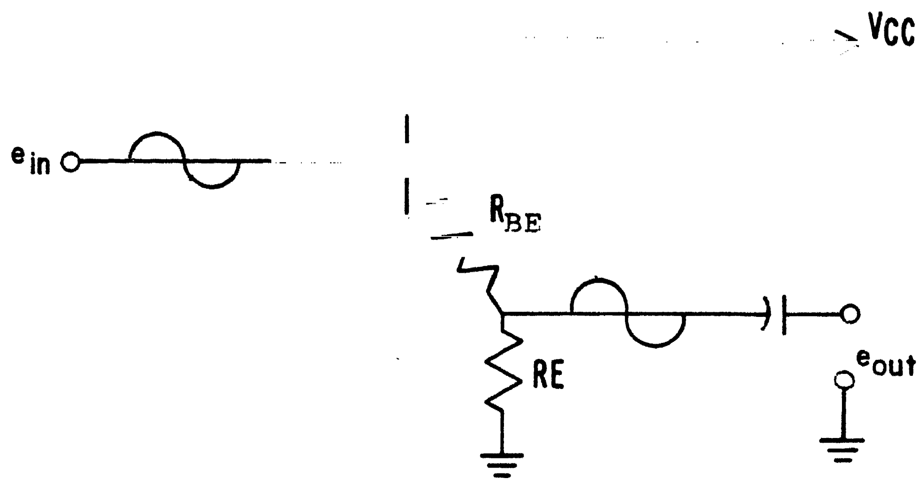
The ratio of the change in output current, I_E, to the change

input current, I_B, or $\frac{\Delta I_E}{\Delta I_B}$ is referred to as "gamma", γ.

6. The voltage gain of the amplifier is always less than 1, although generally it is not much less than 1. The emitter resistor develops the output signal which will be in the same polarity as the input.

7. As can be seen in figure 10, as the input signal goes negative (which would increase forward bias), the output waveform also goes negative, which tries to reduce the forward bias. The actual difference between the input and the output would be the voltage dropped across the forward bias junction R_{BE}.

   Since this resistance is very low, the output voltage will nearly equal the input voltage. In short, what we have is considerable degeneration.



Input Resistance of the Common-Collector Amplifier

Figure 10

8. Power gain is achieved in the stage because of the large current gain, but the gain is less than it is in the common-base or common-emitter characteristics.

9. In summary, the characteristics of the common-collector amplifier are:

   a. There is no polarity inversion between the input and the output. For this reason the common-collector amplifier is frequently referred to as an emitter-follower.

   b. Highest input resistance of the three possible configurations. The input is applied between the collector-base junction which is reverse biased.

   c. The output resistance is very low in the common-collector configuration, the emitter resistor is primarily the load.

   d. The voltage gain is less than 1. You may be wondering: Why use a common-collector stage if the voltage gain is less than unity? Because the input resistance is quite high (approximately 100 k-ohms) and the output resistance quite low (approximately the size of R_E) we can use the common-collector similar to a transformer in that it can be used to transform (step down) the value of load resistance. However, it is quite different from a transformer in that the value of output voltage

is approximately equal to the input voltage, whereas a transformer must step voltage down in order to transform impedance from high to low.

e. There is a high current gain in the common-collector configuration

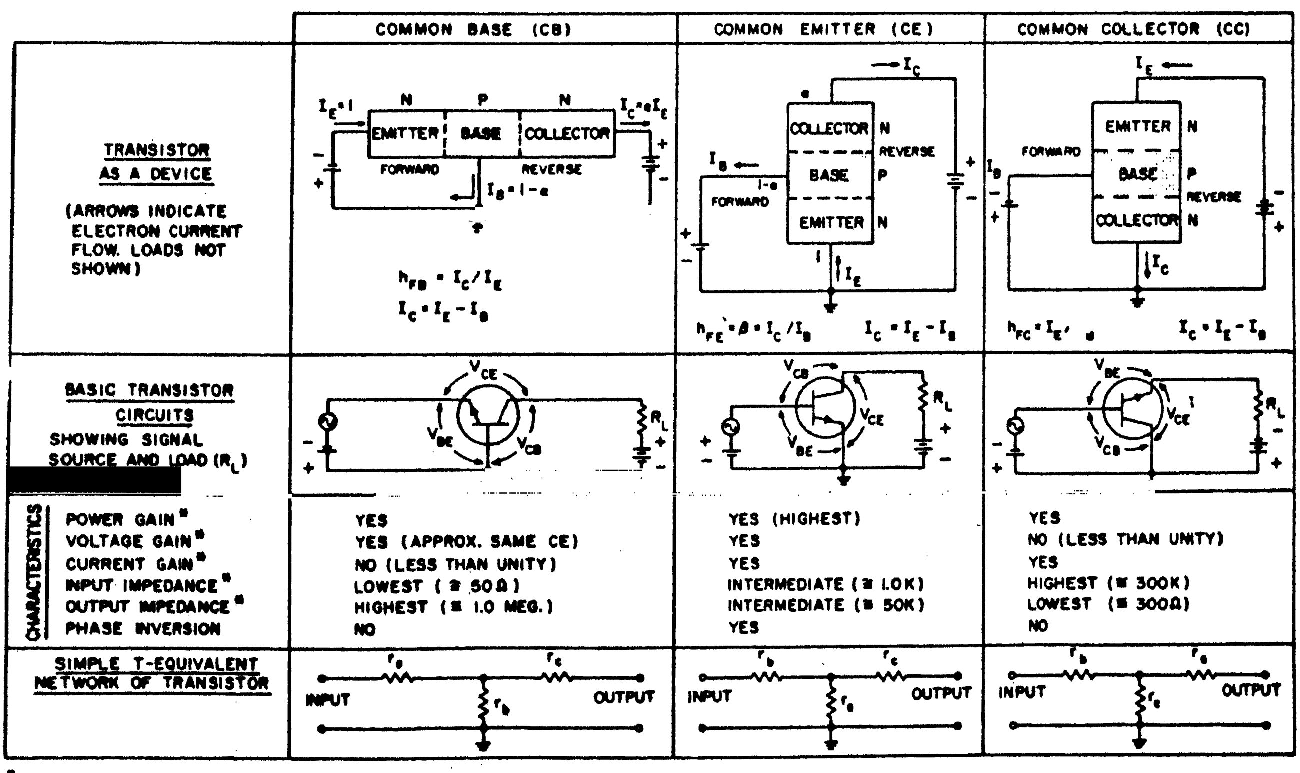
$$\frac{\Delta I_E}{\Delta I_B} = \text{Gamma} = \gamma = (\beta + 1)$$

f. There is a very low power gain in the common-collector amplifier because of the low voltage gain, and low output resistance.

$$P = \frac{E^2}{R}$$

E. Comparisons of amplifier configurations

1. Figure 11 is a table of comparisons of the three amplifier configurations. Note that there are no comparative values given for current gains, voltage gains, or power gains. The reason is quite simple. The actual values of circuit gains (current, voltage, and power) are dependent on the size of the load and the input resistance.



TRANSISTOR CIRCUITS AND CHARACTERISTICS

Figure 11

2. However, it should be remembered that with the proper terminations, the common-base amplifier is capable of the highest voltage gain, the common-emitter the highest power gain, and the common-collector the highest current gain.

III. SPECIFICATIONS

A. An indispensable tool for anyone dealing with the design, operation, or service of electronic equipment is the transistor manual. Here, we find the mechanical and electrical specifications for each type of transistor. In similar fashion, equivalent data is published by transistor manufacturers for each of their products. Transistor manufacturers' sheets contain the specifications of a particular transistor, including maximum ratings, characteristic curves, and physical outline.

1. A typical specification sheet is shown in figures 12 and 13. The various sections of the specifications are numbered 1 to 3, and the appropriate explanations of each will be discussed.

2. We will not cover each specification at this time due to the degree of knowledge on transistors required. However in later lessons, as your knowledge of transistors increases, you will be able to interpret all of the data given by the manufacturer in his specification sheet.

a. The lead paragraph is a general description of the device and usually contains three specific pieces of information: in this instance, an alloy-junction germanium PNP transistor, a few major applications a computers and switching applications, and general features such as standard size and type package.

b. The absolute maximum ratings which must not be exceeded. To exceed them may cause device failure. The dissipation of a transistor is generally limited by the junction temperature (Tj). Therefore, the higher the temperature of the air surrounding the transistor (T_A = ambient temperature), the less power the device dissipates. A factor which indicates how much the transistor must be derated for each degree increase in ambient temperature is usually given. Note that the 2N404 (given on the specifications sheet) can dissipate 150 mW at a T_A of 25°C. By applying the given derating factor of 2.5 mW for each degree increase in ambient temperature, we find that the power dissipation will drop to zero mW at 85°C. This, then, is the maximum operating temperature of the transistor.

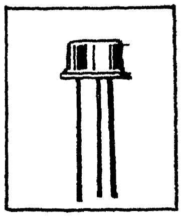
c. All of the electrical characteristics define what the device is capable of under specified test conditions.

(1) "Forward current transfer ratio" is another name for β. In this case, we are talking about an a-c characteristic, so the symbol is h_{fe}. If the d-c Beta is meant, the symbol is H_{FE}. For the 2N404 Beta is 135. This simply means the current gain

$$\frac{\Delta I_C}{\Delta I_B} = 135.$$

TYPES 2N404, 2N404A

HIGH-FREQUENCY TRANSISTORS FOR COMPUTER AND SWITCHING APPLICATIONS



Close parameter control and the JEDEC TO-5 welded package ensure device reliability and stable characteristics

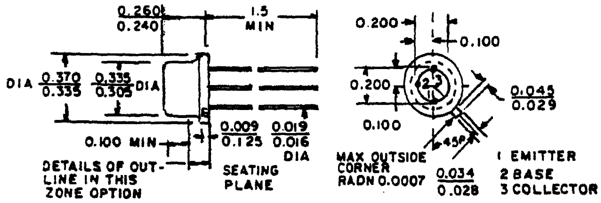
environmental tests

To ensure maximum reliability, stability, and long life, all units are aged at 100°C for 100 hours minimum prior to electrical characterization. All transistors are thoroughly tested for complete adherence to specified design characteristics. In addition, continuous qualification tests are made comprising temperature - humidity cycling, shock and vacuum leak testing under rigid in-process control procedures.

1. mechanical data

Metal case with glass-to-metal hermetic seal between case and leads. Unit weight is approximately 1 gram. These units meet JEDEC TO-5 registration.

All leads insulated from the case.



ALL DIMENSIONS IN INCHES

2. absolute maximum ratings at 25° C free-air temperature (unless otherwise noted)

	2N404	2N404A
Collector-Base Voltage	25v	40v
Collector-Emitter Voltage (see note 1)	24v	35v
Emitter-Base Voltage	12 v	25v
Collector Current	100 ma	150 ma
Emitter Current	100 ma	150 ma
Total Device Dissipation (see note 2)	150 mw	150 mw
Operating Collector Junction Temperature	85°C	100°C
Storage Temperature Range	-65°C to +100°C	-65°C to +100°C

NOTES: 1. Punch through voltage

2. For 2N404 derate linearly to 85°C free-air temperature at the rate of 2.5 mw/°C
For 2N404A derate linearly to 100°C free-air temperature at the rate of 2.0 mw/°C

* Indicates JEDEC registered data.

The maximum power dissipation at 25°C case temperature is 300 mw.

A TRANSISTOR'S SPECIFICATION SHEET

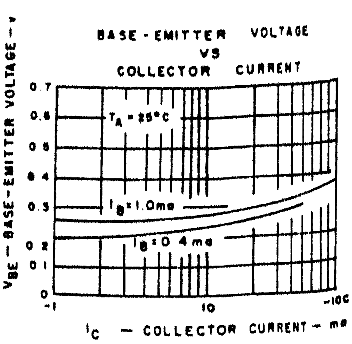
Figure 12.

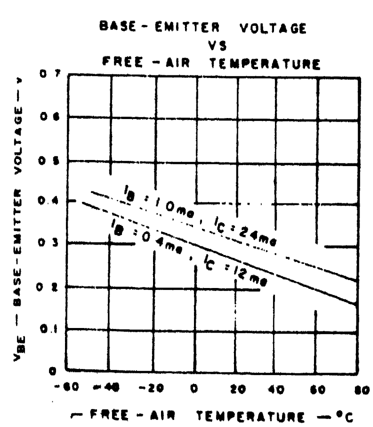
TYPES 2N404, 2N404A P-N-P ALLOY-JUNCTION GERMANIUM TRANSISTORS

ELECTRICAL CHARACTERISTICS AT 25°C FREE AIR TEMPERATURE (UNLESS OTHERWISE NOTED)

PARAMETER	TEST CONDITIONS	2N404 MIN	2N404 TYP	2N404 MAX	2N404A MIN	2N404A TYP	2N404A MAX	UNIT
I_{CBO} COLLECTOR CUTOFF CURRENT	$V_{CB} = -12V$, $I_E = 0$	—	−1	−5*	—	—	−5*	μa
	$V_{CB} = -12V$, $I_E = 0$, $T_A = 80°C$	—	−40	−90*	—	−40	−90*	μa
I_{EBO} EMITTER CUTOFF CURRENT	$V_{EB} = -2.5V$, $I_C = 0$	—	−1	−2.5*	—	−1	−2.5*	μa
BV_{CBO} COLLECTOR-BASE BREAK DOWN VOLTAGE	$I_C = 20\mu a$, $I_E = 0$	−25*	—	—	−40*	—	—	V
BV_{EBO} EMITTER-BASE BREAKDOWN VOLTAGE	$I_E = -20\mu a$, $I_C = 0$	−12*	—	—	−25*	—	—	V
h_{FE} DC FORWARD CURRENT TRANSFER RATIO	$V_{CE} = -0.15V$, $I_C = 12ma$	30	100	—	30	100	—	—
	$V_{CE} = -20V$, $I_C = 24ma$	24	110	—	24	110	—	—
V_{BE} BASE-EMITTER VOLTAGE	$I_B = -0.4ma$, $I_C = -12ma$	—	−0.26	−0.35*	—	−0.26	−0.35*	V
	$I_B = -1ma$, $I_C = -24ma$	—	−0.30	−0.40*	—	−0.30	−0.40*	V
$V_{CE(sat)}$ COLLECTOR-EMITTER SATURATION VOLTAGE	$I_B = -0.4ma$, $I_C = -12ma$	—	−0.06	−0.15*	—	−0.06	−0.15*	V
	$I_B = -1ma$, $I_C = -24ma$	—	−0.08	−0.20*	—	−0.08	−0.20*	V
V_{PT} PUNCH-THROUGH VOLTAGE †	$V_{EBfl} = -1V$	−24*	—	—	—	—	—	V
V_{EBfl} EMITTER-BASE FLOATING POTENTIAL	$V_{CB} = -35V$	—	—	—	—	−0.2	−1	V
h_{fe} AC COMMON-EMITTER FORWARD CURRENT TRANSFER RATIO	$V_{CE} = -6V$, $I_C = -1ma$, f = 1KC	—	135	—	—	135	—	—
h_{ie} AC COMMON EMITTER INPUT IMPEDANCE	$V_{CE} = -$, $I_C = -1ma$, f = 1KC	—	4	—	—	4	—	Kohm
h_{oe} AC COMMON-EMITTER OUTPUT ADMITTANCE	$V_{CE} = -6V$, $I_C = 1ma$, f = 1KC	—	50	—	—	50	—	μmho
h_{re} AC COMMON-EMITTER REVERSE VOLTAGE TRANSFER RATIO	$V_{CE} = -6V$, $I_C = 1ma$, f = 1KC	—	7×10^{-4}	—	—	7×10^{-4}	—	—
C_{ob} COMMON-BASE OUTPUT CAPACITANCE	$V_{CB} = -6V$, $I_E = 0$, f = 1MC	—	9	20*	—	—	—	pf
	$V_{CB} = -6V$, $I_E = 1ma$, f = 2MC	—	—	—	—	9	20*	pf
f_{hfb} COMMON-BASE ALPHA CUTOFF FREQUENCY	$V_{CB} = -6V$, $I_E = 1ma$	4*	12	—	4*	12	—	MC

†V_{PT} IS DETERMINED BY MEASURING THE EMITTER-BASE FLOATING POTENTIAL V_{EBFl}
USING A VOLTMETER WITH 11 MEGOHMS MINIMUM INPUT IMPEDENCE THE COLLECTOR-BASE
VOLTAGE, V_{CB} IS INCREASED UNTIL $V_{EBFl} = -1$ VOLT; THIS VALUE OF $V_{CB} = (V_{PT} + 1)$ CARE MUST
BE TAKEN NOT TO EXCEED MAXIMUM COLLECTOR-BASE VOLTAGE SPECIFIED UNDER MAXIMUM
RATINGS.





A TYPICAL SPECIFICATION SHEET

Figure 13

(2) The frequency cutoff (f_{hfb}) of a transistor is that frequency at which the common-base current gain drops to 0.707 of the 1000 Hz value. It gives a rough indication of the useful frequency range of the device.

(3) The collector breakdown voltage BV_{CBO} is the reverse bias voltage between the collector and base with the emitter open at which there is a sharp increase in current flow between the collector and base. This point is known as the avalanche breakdown, in which minority electrons, passing the PN junction, gain sufficient energy to knock off valence electrons bound to the crystal lattice and raise them to the conduction band. BV_{CBO} is usually specified at some value of reverse leakage current. The 2N404 will avalanche between the collector and base at approximately 25 volts with 20 µamps of leakage current.

(4) Emitter breakdown voltage BV_{EBO} is the maximum voltage which can be safely applied between emitter and base when these elements are reverse biased with the collector open. This value is given in specification sheets in order to indicate how large a reverse bias voltage may be applied to the input of a common-emitter amplifier before the input circuit will break down.

(5) Many manufacturers will list a collector saturation voltage $V_{CE}(sat)$. This voltage is essentially the minimum voltage necessary, at a particular collector current, to sustain normal transistor action, and it occurs when the emitter-base voltage equals the emitter-collector voltage. At lower collector voltages, the base-collector junction becomes forward biased and the current-voltage relationship changes abruptly. The current will increase at a rapid rate limited only by any external resistance in the collector circuit.

(6) The collector cutoff current is the current from collector to base when no emitter current is being applied. This is I_{CBO}. It varies with temperature changes and must be taken into account whenever a semiconductor is designed into equipment which is used over a wide range of ambient temperatures.

(7) Base to emitter voltage V_{BE} is the voltage that is recommended by the manufacturer for normal transistor action. Notice for the 2N404 V_{BE} is listed for typical and maximum conditions. For normal operation, the static value of V_{BE} should

be approximately -.26V. The maximum value of V_{BE} is that forward bias voltage which would saturate the transistor. Applying more than -.35 volts forward bias to the 2N404 would lead to distortion in the output.

B. In summary, there are many characteristics of a transistor made available to us by the manufacturer. We have discussed only a few of the characteristics but, as stated earlier, in future lessons you will become familiar with several more important transistor characteristics.

1. Probably the two most important characteristics we have discussed were the maximum reverse bias between collector and base (BV_{CBO}), and the power dissipation rating.

2. The power dissipation rating of the 2N404 (150 mW) was actually another way of expressing the safe amount of heat which the collector-base junction can withstand.

3. In other words, the transistor must dissipate power in the form of heat across the junction. If the power is too great, there will be more than 85°C of heat generated at the junction, which would destroy the device. It was found that we must derate (reduce the output power) the transistor for each degree of increase in ambient temperature as the collector-base junction must dissipate the heat it receives to the ambient air.

4. To assist transistors in achieving higher collector-dissipation ratings, heat sinks, in which the transistors are mounted, have been developed. These heat sinks, or heat dissipaters, help conduct heat away from the junction, thus lowering the junction temperature (Tj).

NOTETAKING SHEET 2.6.1N

JUNCTION TRANSISTORS

REFERENCES:

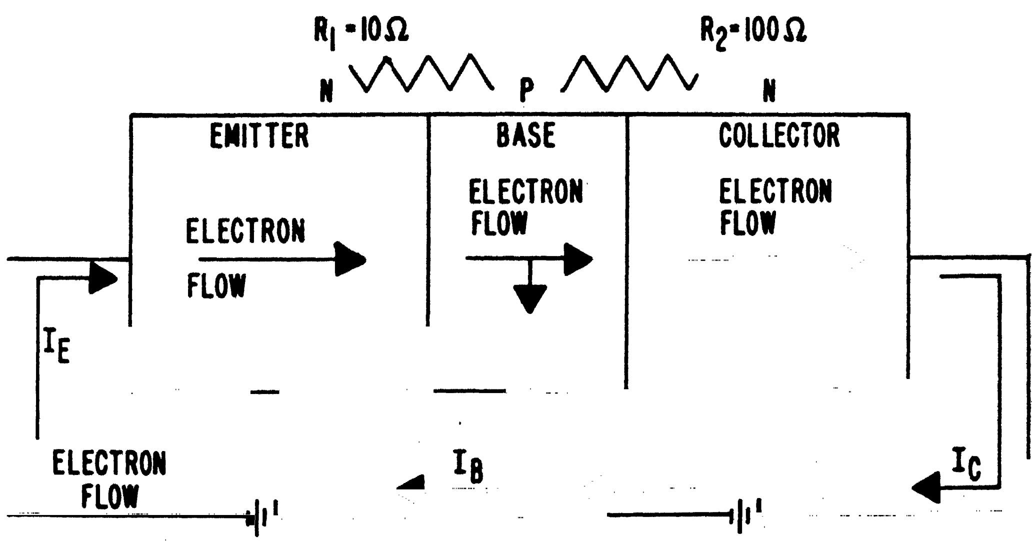
1. Electronic Circuits, NAVSHIPS 0967-00-0120, pp. 5-10 to 5-20.

2. Essentials of Radio-Electronics, Slurzburg and Osterheld, McGraw-Hill Co.

3. Transistor and Integrated Electronics, Kiver, McGraw-Hill Co., 1972, Fourth Edition.

NOTETAKING OUTLINE:

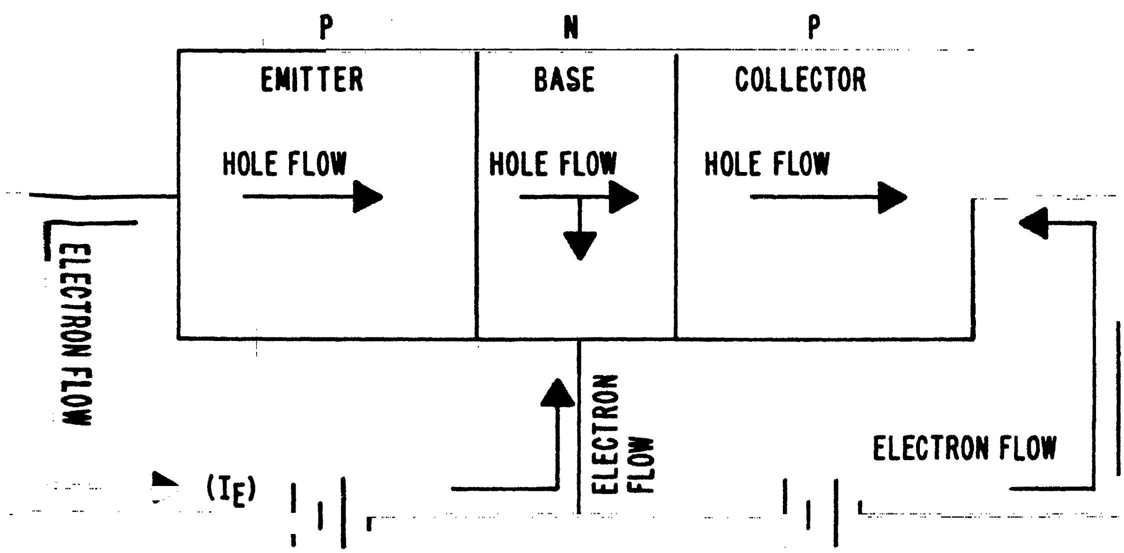
I. Transistor action



2.6 Figure 1 - NPN Transistor

A. Analysis of the NPN Transistor

B. Analysis of the PNP Transistor

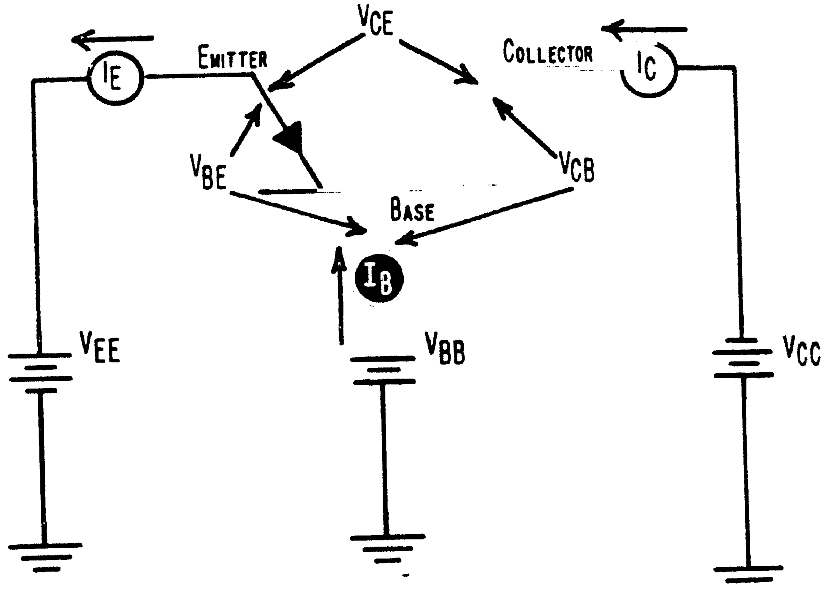


2.6 Figure 2 - PNP Transistor

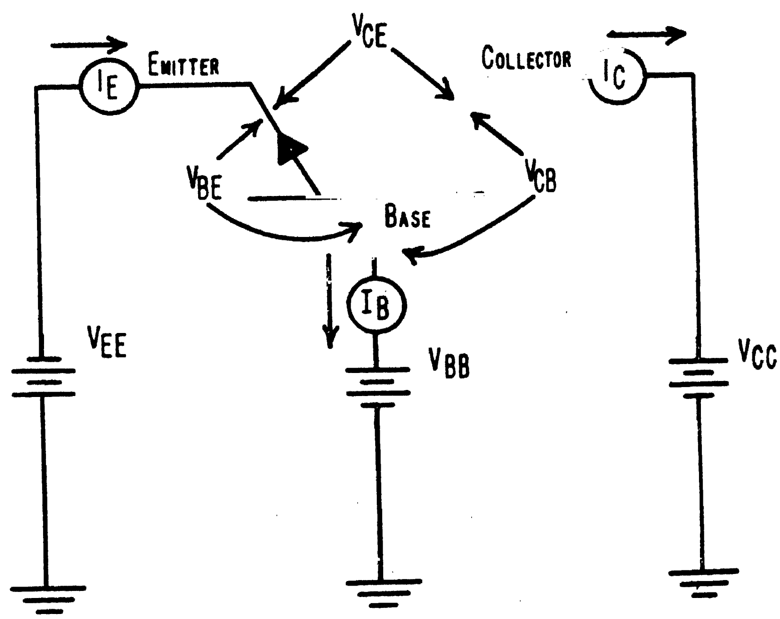
C. Mechanisms of transistor action

II. Transistor symbology and notations

A. Schematic symbols



A. PNP Transistor



B. NPN Tra

2.6 Figu

B. Operating potentials

1. NPN type

2. PNP type

3. Supply voltages

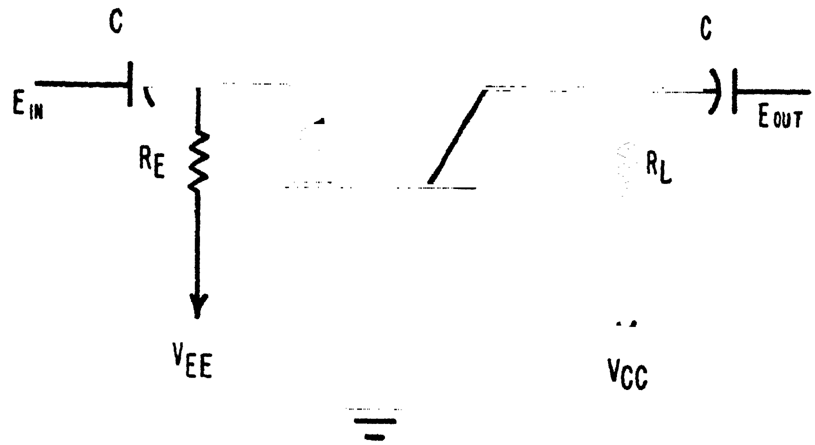
4. Terminal voltages

5. Terminal currents

III. Circuit configurations and operation

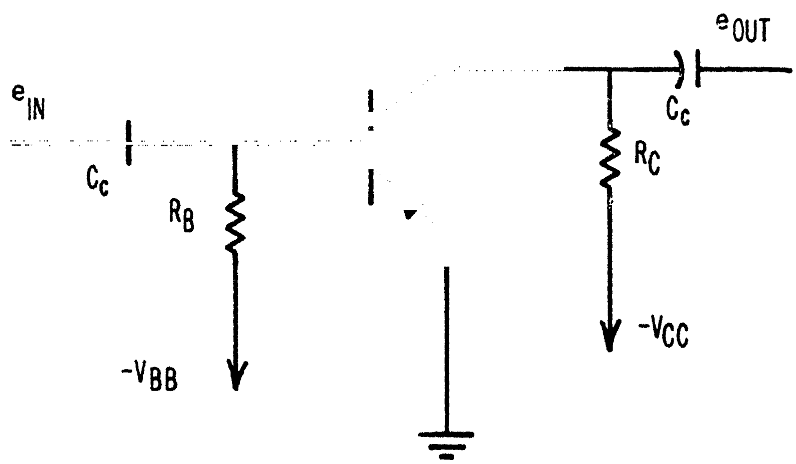
A. Three basic configurations

B. Common-base amplifier



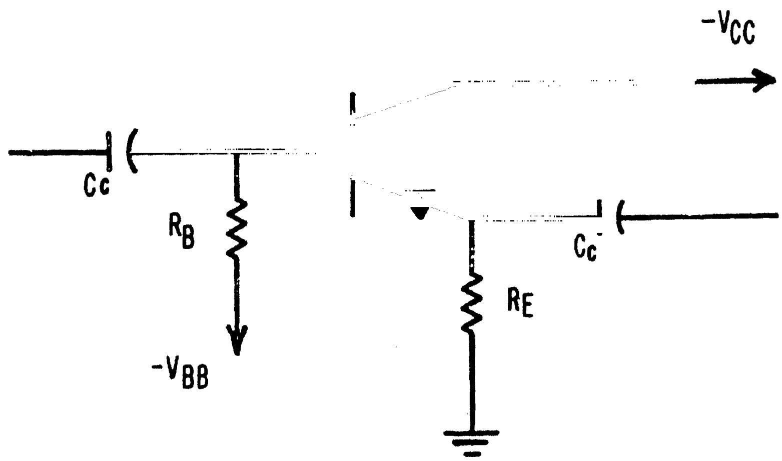
2.7 Figure 4 - Common-Base Amplifier (PNP)

C. Common-emitter amplifier



2.6 Figure 5 - Common-Emitter Amplifier (PNP)

D. Common-Collector amplifier



2.6 Figure 6 - Common-Collector Amplifier (PNP)

IV. Specifications

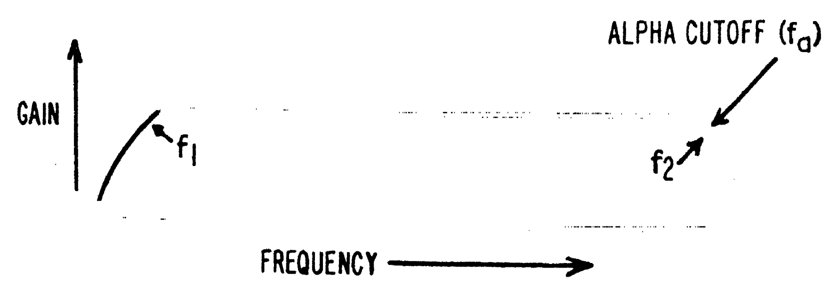
A. Maximum reverse-bias voltage

B. Junction temperature

C. Decreased current gain at high levels of transistor current.

D. Noise

E. Frequency response



2.6 Figure 7 - Transistor Frequency Response Curve

DATA SHEET 2.7.1D

JUNCTION TRANSISTOR LABORATORY

INTRODUCTION

The purpose of this data sheet is for you to measure, record, and compare the d-c gains and resistances of the three basic transistor configurations.

1. Common-base amplifier

a. Complete the following schematic of the common-base amplifier and label components; i.e., V_{CC}, V_{EE}, R_E, R_L, etc.

b. Static measurements and calculations:

(1) I_E = ____________

(2) V_{EB} = ____________

(3) I_B = ____________

(4) V_{CB} = ____________

(5) I_C = ____________

(6) R_I = ____________

(7) $A_I(\alpha)$ = ____________

c. Dynamic measurements

(1) e_{out} = ____________

(2) e_{in} = ____________

(3) A_v = ____________

d. Questions:

(1) Write the formula for V_{EB} for the above schematic.

V_{EB} = ____

(2) What would increasing the size of R_C (R_L) do to the A_v?

____

(d) Are the bias voltages correct for normal transistor operation?

____

Instructor's initials ___

2. Common-collector amplifier

a. Complete the following schematic of the common-collect amplifier and label components.

b. Static measurements and calculations:

(1) V_B = ______________

(2) V_C = ______________

(3) V_E = ______________

(4) I_B = ______________

(5) V_{BC} = ______________

(6) V_{BE} = ______________

(7) I_E = ______________

(8) R_I = ______________

(9) $A_I(\gamma)$ = ______________

amic measurements:

out = ______________

= ______________

____

d. Questions

(1) What would happen to A_V if R_E increased in size?

____

(2) Are the bias voltages correct for normal transistor operation?

____

(3) What is the voltage gain characteristic of the common-collector amplifier? ______________________________

Instructor's initials ________

3. Common-emitter amplifier

a. Complete the following schematic of the common-emitter amplifier and label components.

b. Static measurements and calculations:

(1) V_E = ______________

(2) V_B = ______________

(3) V_C = ______________

(4) I_B = ______________

(5) V_{BE} = ______________

(6) I_E = ______________

(7) I_C = ______________

(8) R_I = ______________

(9) A_I (β) = ________

c. Dynamic measurements:

(1) e_{out} = ______________

(2) e_{in} = ______________

(3) A_v = ______________

d. Questions

(1) What would happen to forward bias if R_E were increa

____

(2) Are the bias voltages correct for normal temperatur operation?

____

Instructor's initials ______

INFORMATION SHEET 2.8.1I

BIASING ARRANGEMENTS

INTRODUCTION

Biasing a transistor means setting the d-c voltages and currents of the transistor to certain chosen values to establish an operating point for the a-c signal. A bias circuit employs resistors and d-c power supplies to set the various voltages and currents at the predetermined values. These d-c voltages and currents must be such that none of the transistor's ratings are exceeded; that is, they must be within the permissible operating point region.

REFERENCES

1. Electronic Circuit Analysis, NAVAIR 00-80-T-79, Chapter 8.

2. Milton S. Kiver, Transistor and Integrated Electronics. New York, N. Y., McGraw-Hill Book Company, 1972, Fourth Edition.

INFORMATION

A. Introduction

1. When the a-c signal is applied to the transistor, the transistor's voltages and currents vary about the operating point. Only a portion of the permissible operating point region is such that the amplification is linear; this portion of the permissible operating point region is called the linear operating region. The entire signal swing must be within the linear operating region for the input to be amplified without appreciable distortion.

2. There are two major reasons for the difficulty in sustaining a desired operating point. First, as was noted in "Introduction to Semiconductors," the characteristics of semiconductor materials are temperature dependent. Second, the characteristics of different transistors of the same type will vary from unit to unit. Consequently, when various transistors are placed in the same circuit, the operation will vary somewhat unless stabilizing measures are taken.

B. Temperature variation - The transistor characteristics spec by a manufacturer are usually valid only for a given ambien temperature (usually 25°C). The actual junction temperatur a transistor depends upon both the power dissipated in the transistor and the means for removing heat from the transis Changes in temperature affect three transistor quantities: *I_{CBO}, β, and V_{EB}. β and I_{CBO} will rise as the temperature increases. The V_{EB} which is necessary to produce a given emitter current decreases as the temperature increases. Of these, the most serious variation is experienced by I_{CBO}.

1. Reverse-Bias Collector Current (I_{CBO}). I_{CBO} (sometimes referred to as I_{CO}) is normally measured at a T_A (ambie temperature) of 25°C (see figure 1). Note that I_{CBO} is minority current, and flows in the same direction as collector current if the transistor was properly biased This current I_{CBO}/I_{CO} is the same type current (minorit that flows in any PN junction under a reversed biased condition (see figure 2). The current flow in the reve biased condition is almost constant and independent of voltage prior to the breakdown point.

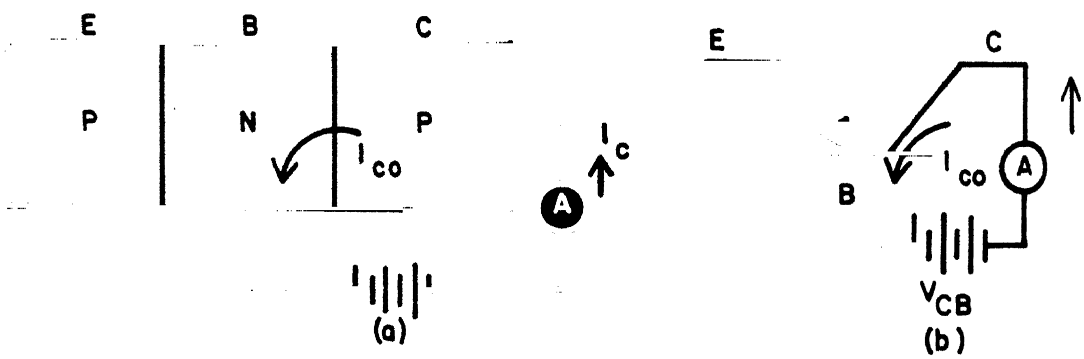
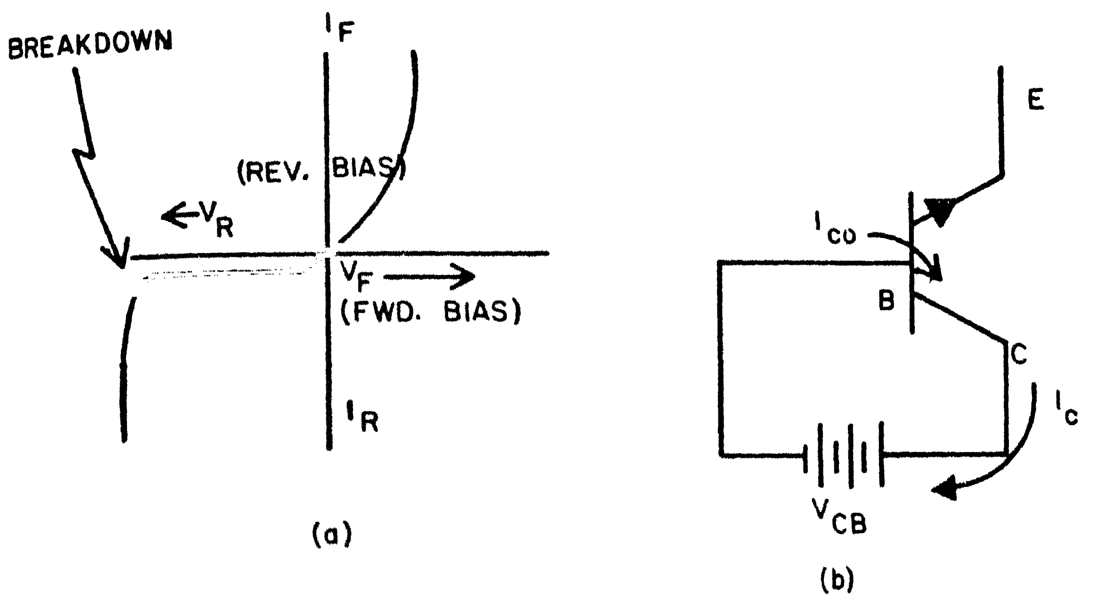


Figure 1

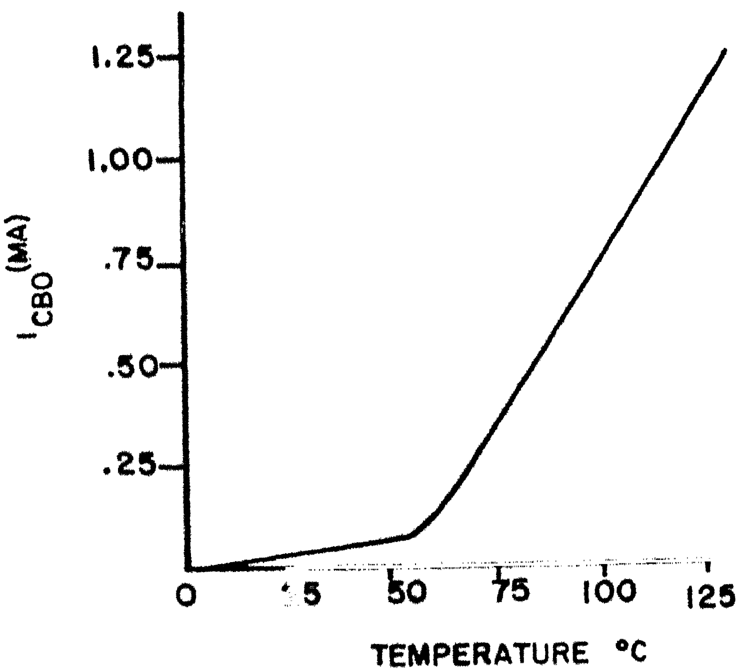
a. Variations of I_{CBO}/I_{CO} with temperature of the collector-base junction is shown in figure 3. The current value varies from almost zero at 10°C to well over 1 milliampere at 125°C. Note that at temperatures below 10°C, I_{CBO} causes no problem. I_{CO} doubles for every 10°C rise in germanium, and every 6°C rise in silicon.

: when collector-base junction is the emitter is open circuited.



PN Junction Characteristics

Figure 2



I_{CBO} as a function of temperature

Figure 3

b. In a PNP transistor, I_{CBO} consist of electrons (minority carriers) flowing from the collector (figure 1) toward the base. If the resistivity of the base, or if external resistors connected to the base are high in value, electrons from the collector can accumulate in the base region. Such an accumulation of electrons will cause an increase of emitter hole into the base, increasing collector current. Increased collector current would raise the temperature of the collector-base junction, and cause an increase in I_{CO} (figure 3). The cycle would continue until severe distortion occurs, the transistor becomes inoperative, or it destroys itself. THIS CONDITION CAN BE MINIMIZED BY AVOIDING THE USE OF HIGH-VALUED RESISTORS IN THE BASE LEAD.

2. Beta - β is the current gain of the common-emitter transistor configuration. It is the ratio of a change in collector current (ΔI_C) caused by a change in base current (ΔI_B). I_{CBO} flows through the base lead in opposite direction to I_B (figure 4), increases I_{CBO}, causes I_C to increase, and I_B to decrease. Therefore, for a set value of I_B β would increase and shift the operating point.

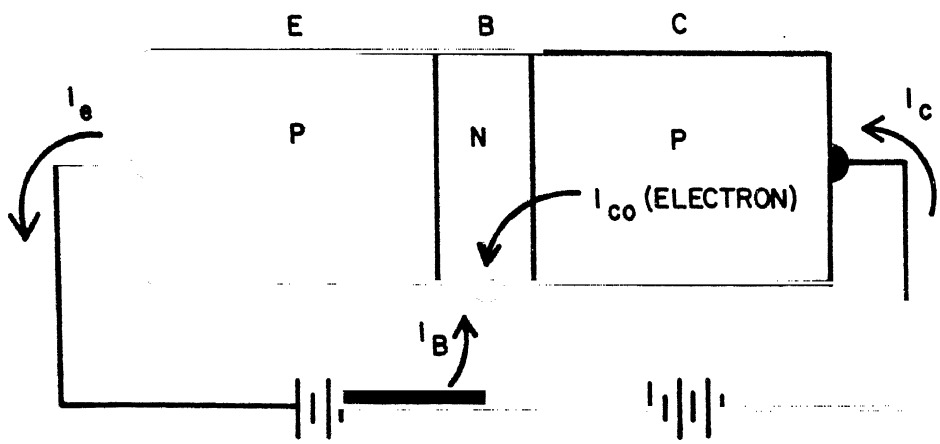
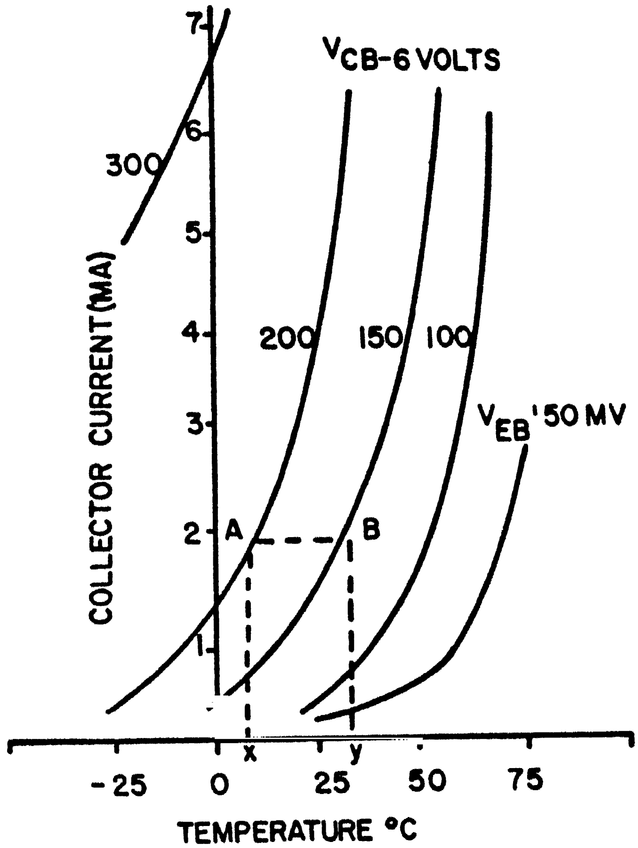


Figure 4

3. V_{EB} - Figure 5 indicates the variation of collector current with temperature. Each curve is plotted with a fixed collector-base voltage (V_{CB}) and a fixed emitter-base voltage (V_{EB}). If the collector current variation with temperature were caused only by I_{CBO} (figure 3), then the collector current variation at temperature below 10°C (V_{EB} = 200 mV and V_{EB} = 300 mV) should not occur. However, collector current does vary with temperature, even when I_{CO}

is near zero. This variation is caused by the decrease in emitter base junction resistance when the temperature is increased. That is, the emitter-base junction resistance has a NEGATIVE TEMPERATURE-COEFFICIENT of resistance.



Variation of Collector Current with Transistor Temperature

Figure 5

a. One method of reducing the effect of the NEGATIVE TEMPERATURE COEFFICIENT of resistance is to place a large value resistor in the emitter lead. Essentially, this causes the variation of emitter-base junction resistance to be a small percentage of the total re-resistance in the emitter circuit. The external resistor swamps (overcomes) the junction resistance; the resistor is referred to as a swamping resistor.

b. A second method of reducing the effect of the negative temperature coefficient of resistance is to reduce the emitter-base forward bias as the temperature increases. For instance, to maintain the collector current at 2 mA (figure 5) while the transistor temperature varies from 10°C (at X) to 30°C (at Y), the forward bias must be

reduced from 200 mV (at A) to 150 mV (at B). The temperature difference is 20°C; the voltage difference is 50 mV. The variation in forward bias per degree centigrade is calculated as follows:

$$\frac{\text{Difference in forward bias}}{\text{Difference in temperature}} = \frac{50 \text{ mV}}{20\,^\circ\text{C}} = 2.5 \text{ mV}/^\circ\text{C}$$

This calculation indicates that collector current will not vary with emitter-base junction resistance if the forward bias is reduced 2.5 mV/°C for increasing temperature, or increased 2.5 mV/°C for decreasing temperature.

C. Common-Emitter Amplifier

1. The common-emitter amplifier is the most commonly used amplifier because it has the following characteristics:

   a. Current gain; $\beta = \frac{\alpha}{1-\alpha}$

   b. Voltage gain $\cong \beta \cong \frac{R_o}{R_i}$

   c. Highest power gain

   d. Easier to cascade because $\frac{R_o}{R_i}$ is more closely matched.

   However, it must be stabilized because of unit to unit variations, and temperature instability.

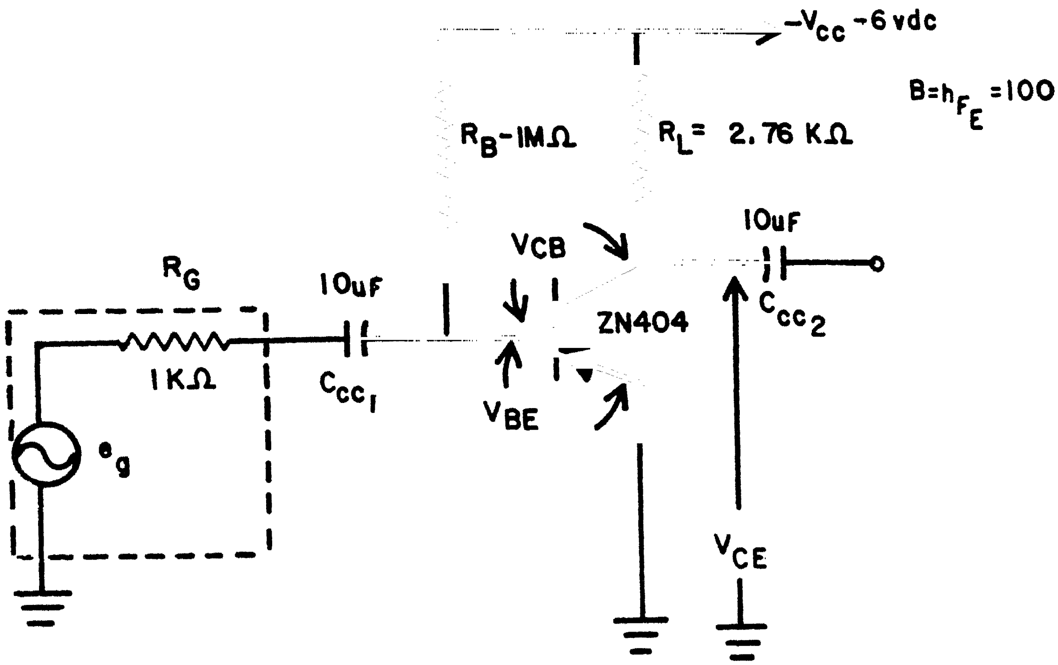
   (1) There are several biasing arrangements used on the common-emitter amplifier to compensate for its instability. Constant base current biasing is shown in figure 6 and will be used to analyze basic biasing.

$$I_B = \frac{V_{CC} - V_{BE}}{RB} = \frac{5.8V}{1M} = 5.8 \ \mu A \qquad \text{(Eq 1.1}$$

$V_{BE} \approx .2V$ for germanium; since $R_B >>$ the d-c input resistance, I_B will be limited primarily by R_B.

$$I_C = \beta I_B = 100 \times 5.8 \ \mu A \qquad \text{(Eq 1.2}$$

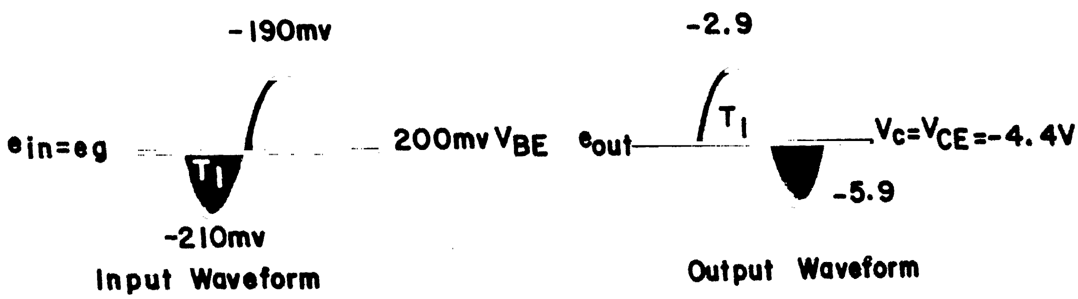
$$\begin{aligned} V_{CE} &= V_{CC} - V_{RL} = V_{CC} - I_C R_L \qquad \text{(Eq 1.3} \\ &= 6 \text{ volts} - (.58 \text{ mA})(2.76 \text{ k}\Omega) \\ &= 6 - 1.6 = 4.4 \text{ volts} \end{aligned}$$



Constant-base-current bias common-
emitter amplifier

Figure 6

Therefore, the collector voltage $V_C = V_{CE}$ is 4.4 volts. The output waveform will vary around this point (4.4 volts) as shown in figure 7.



$$A_v = \frac{e_{out}}{e_{in}} = \frac{3.0v}{20mv} = 150 \qquad \text{Eq (1.5)}$$

Output waveform versus input waveform

Figure 7

$$V_{CB} \text{ (reverse bias)} = V_C - V_B = -4.4V - (-.2V) \quad \text{Eq 1.4)}$$

$$= 4.2V$$

Assume a voltage gain of 150 and e_{in} of 20 mV peak-to-peak, the output would be symmetrical.

(2) However, the picture is incomplete because the d-c parameter I_{CBO} was not included. I_{CBO} is a minority current that flows collector to base with the emitter open. However, transistor action cannot occur with the emitter open. If, on the other hand, I_{CBO} flowed only in the collector-base circuit, it would cause no serious problem. But, if a circuit is constructed that has a high resistance in the base lead, it will appear open to this minority current. This will cause a current to flow called I_{CEO}* (figure 8). These minority carriers enter the base

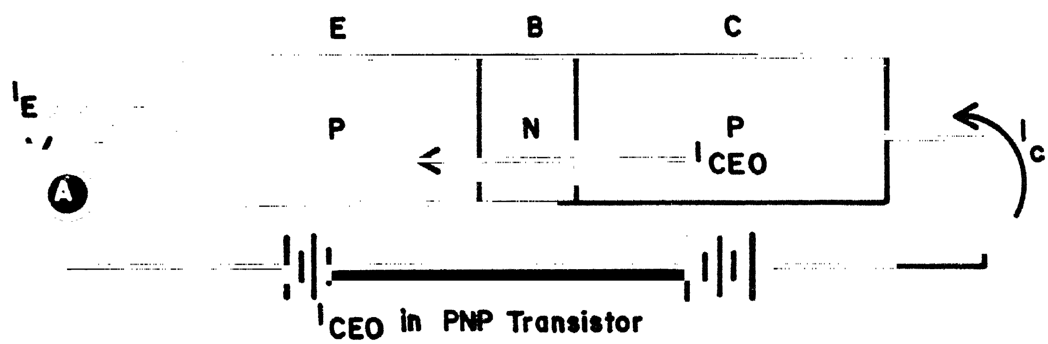


Figure 8

circuit and become majority carriers. To the common emitter, this is the same as an increase in forward bias current. The emitter injects $\beta + 1$ holes into the base to offset the negative charge in the base. β holes will diffuse through the base and 1 is the amount that will recombine with I_{CO}.

Mathematically:

$$I_{CEO} = I_{CBO}\,(B+1) = I_{CO}(B+1) \qquad \text{(Eq 1.6)}$$

The collector current (I_C) is:

$$I_C = \beta I_B \text{ (Eq 1.2)} + I_{CEO} \qquad \text{(Eq 1.6)}$$

$$= \beta I_B + I_{CEO}$$

$$= \beta I_B + I_{CO}(B+1)$$

*I_{CEO} - Minority current that flows collector to emitter with the base open.

Returning to figure 6, I_{CO} for the transistor is assumed to be 5 μA. Therefore:

$$I_C = \beta I_B + I_{CO}(B+1)$$

$$= (100)(5.8\ \mu A) + 5\ \mu A\ (101)$$

$$= (1.085\ mA)$$

$$V_C = V_{CC} - I_C R_L = 6 - (1.085\ mA)(2.76\ k\Omega) \qquad \text{(Eq 1.8)}$$

$$= 6 - 2.99 \approx 3 \text{ volts}$$

The actual operating point would be V_{CE}=3 volts and again the output signal would be symmetrical if the input remained 20 mV p-p and A_v 150. However, if the temperature increases and cause I_{CO} to increase, I_C will increase. This would create more heat and more I_{CO}. This process is called thermal runaway and could damage the transistor if R_L is very small. In our example, if the temperature increased and caused I_{CO} to increase to 15 μA, a small current compared to I_C, the new operating point will be:

$$V_{CE} = V_{CC} - I_C R_L \qquad \text{(Eq 1.9)}$$

$$= V_{CC} - \{100 \times 5.8\mu A + (15\mu A)(101)\}(2.76\ k\Omega)$$

$$= 6 - 5.78$$

$$= -.22V \text{ (saturation)}$$

If the input signal and A_v remained the same, then:

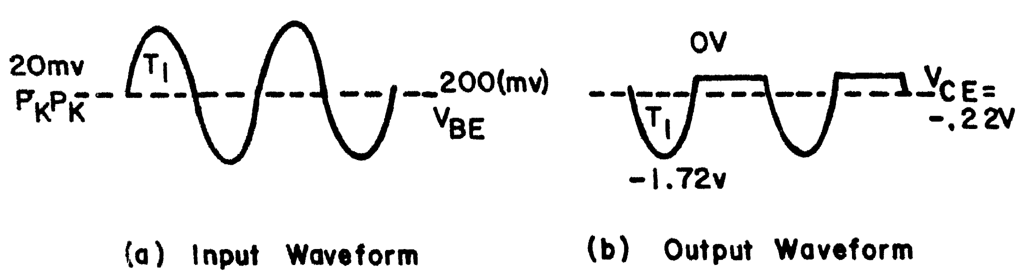


Figure 9

serious distortion would result, the collector base junction is forward biased, a saturated condition. The operating point has shifted from approximately 3 volts to .22 volts.

2. Stability factor

a. A measure of the sensitivity of the operating point to temperature changes is given by the stability factor (S) where S is defined as:

$$S = \frac{\Delta I_C}{\Delta I_{CBO}} \qquad \text{(Eq 1.10)}$$

It indicates the change in collector current (I_C) per change in I_{CBO}. The optimium value of S is 1. If S equals 1, then I_C will change only by the change in I_{CBO}. This is an idealized objective and is not realizable with ordinary measures. The value of S is always greater than 1 for the common-emitter amplifier. However, it should be remembered that the closer the value of S is to 1, the better.

Apply equation 1.10 to figure 6.

$$S = \frac{\Delta I_C}{\Delta I_{CBO}} = \frac{\Delta I_{CEO}}{\Delta I_{CO}} = \frac{1{,}010\,\mu A}{10\,\mu A} = 101 = \beta + 1$$

The stability factor of the unstabilized common emitter amplifier (figure 6) approximately equals the d-c current gain. We will see in the following circuits how this value is improved by various stabilizing schemes.

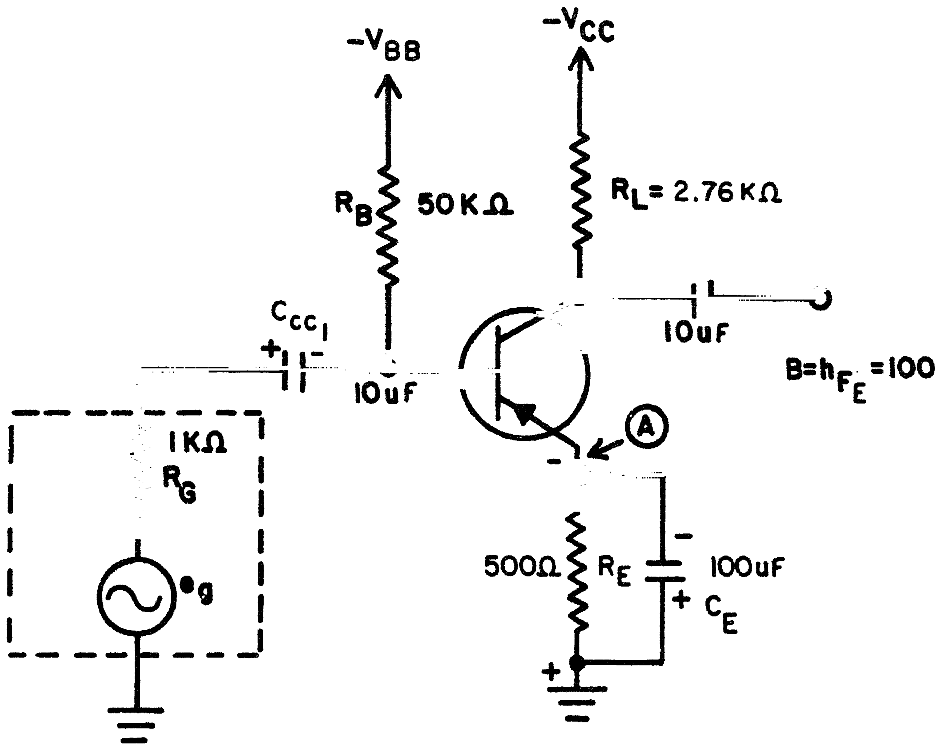
b. Figure 10 is a bias scheme used to improve the stability of the circuit. The addition of an emitter resistor (swamping resistor) increases the stability of the circuits by:

(1) Compensating for the negative coefficient of resistance of the emitter base junction.

(2) Unit to unit variations, since this variation is the same as temperature variations.

(3) Providing a constant current source.

The resistor R_E adds the disadvantage of decreased gain since it develops a voltage that is degenerative to the input signal. If greater gain is required it can be bypassed with a capacitor. R_B is reduced to 50 kΩ. This bias scheme is called constant emitter current biasing, since it attempts to maintain I_E constant. An increase in I_E would cause a more negative voltage to be developed at point (A) in figure 10, which would decrease the forward bias and reduce transistor current. Conversely, any decrease in I_E would increase forward bias and increase transistor current. The net result is a relatively constant current (d-c current) within the



Constant Emitter Current Biased Common Emitter Amplifier

Figure 10

limits of the circuit. Under dynamic conditions, the emitter is at a-c ground due to the bypassing action of C_E. It should be remembered that bias stability deals with d-c conditions and C_E simply keeps the emitter at a-c ground. Through the use of calculus it can be proven that the stability factor for the circuit in figure 10 is

$$S = \frac{\Delta I_C}{\Delta I_{CBO}} = \frac{(R_B+R_E)(\beta+1)}{R_B+(1+\beta)R_E} \qquad \text{(Eq 1.11)}$$

$$= \frac{(50\times10^3 + .5\times10^3)(101)}{50\times10^3 + (.5\times10^3)(101)}$$

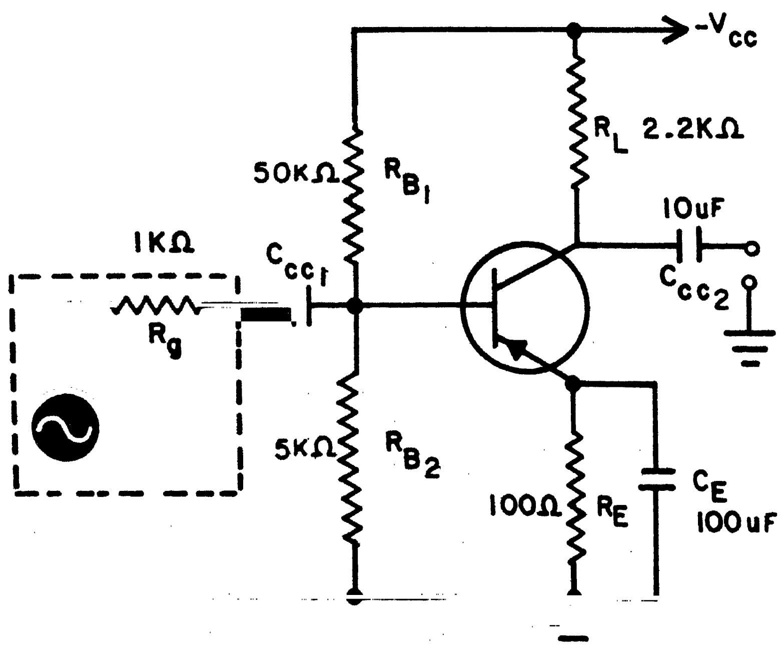
$$= \frac{5100.5 \times 10^3}{100.5 \times 10^3}$$

$$= 50.75$$

c. The stability factor of 50.75 is a considerable improvement over constant-base-current biasing. Equation 1.11 shows that as resistance in the base lead approaches zero, the stability factor approaches ideal. Further, if R_E approaches zero the stability factor approaches B+1. Therefore, for good stability R_B should be as small as possible and R_E as large as possible. One cannot make R_E larger and R_B smaller indefinitely; however, even though R_E can be a-c bypassed by a capacitor, the power supply voltage must be made larger as R_E is increased. For R_B, a lower limit set by the shunting effect on the a-c signal if the stage is capacitive or direct coupled; if it is transformer coupled, the lower limit on R_B is set only by the magnitude of the bias voltage.

d. The stability, it is noted, is affected by R_E, R_B, and Beta of the transistor. Note also, that the stability does not depend on R_L. The stability factor used in any circuit will depend on whether the I_C variation is permissible, in terms of signal swing, permissible power dissipation, or the conditions for thermal runaway. If not, then R_E must be raised or R_B lowered until a suitable condition is found.

e. The most frequently used biasing circuit is shown in figure 11 where an additional resistor is added in the base circuit.



Beta = 1

$$S = \frac{(R_B + R_E)(B + 1)}{R_B + (1 + B)\ R_E}$$

$$R_B = \frac{(R_{B1})(R_{B2})}{R_{B1} + R_{B2}}$$

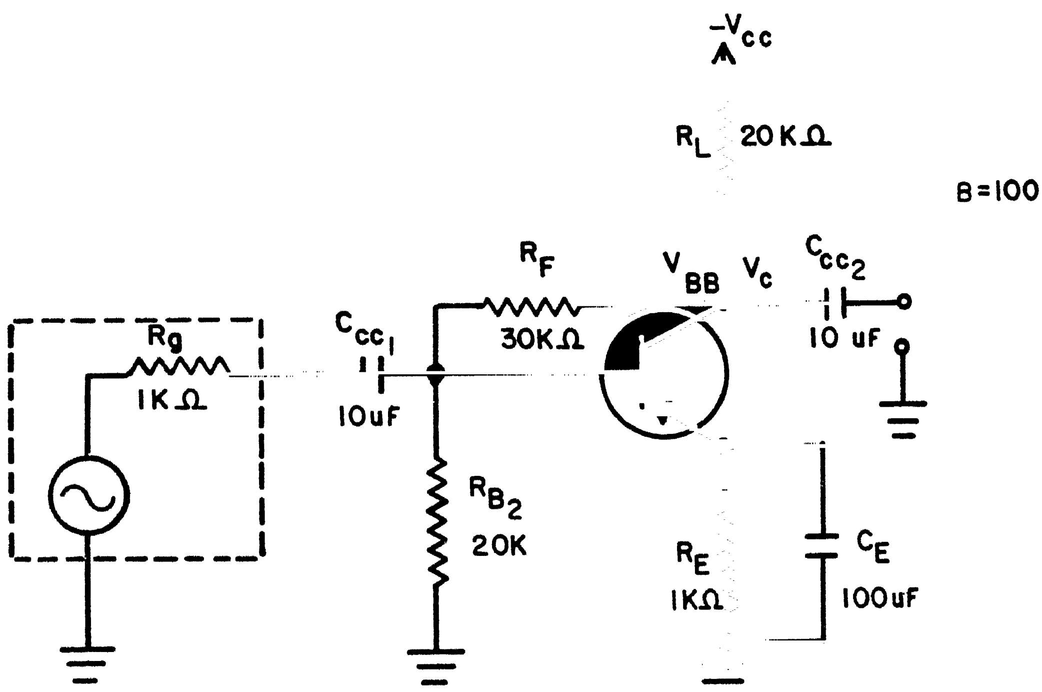
Constant Base Voltage

Figure 11

Equation 1.11 applies to this circuit. R_{B1} normally >> R_{B2}; in effect R_{B2} determines the stability. An advantage as compared to figure 10 is the use of one power supply. If a single power supply was used in figure 10, R_B would be large to establish the proper forward bias. This would decrease the stability of the circuit.

f. In figures 10 and 11, the swamping resistor develops degenerative d-c current feedback. If a-c stability is also desired, the removal of the emitter bypass capacitor (C_E) will provide a-c current feedback.

g. Another general method for stabilizing the operating point consists of using direct voltage feedback with direct current feedback (figure 12).



Constant-Collector-Voltage Biased
Common-Emitter Amplifier

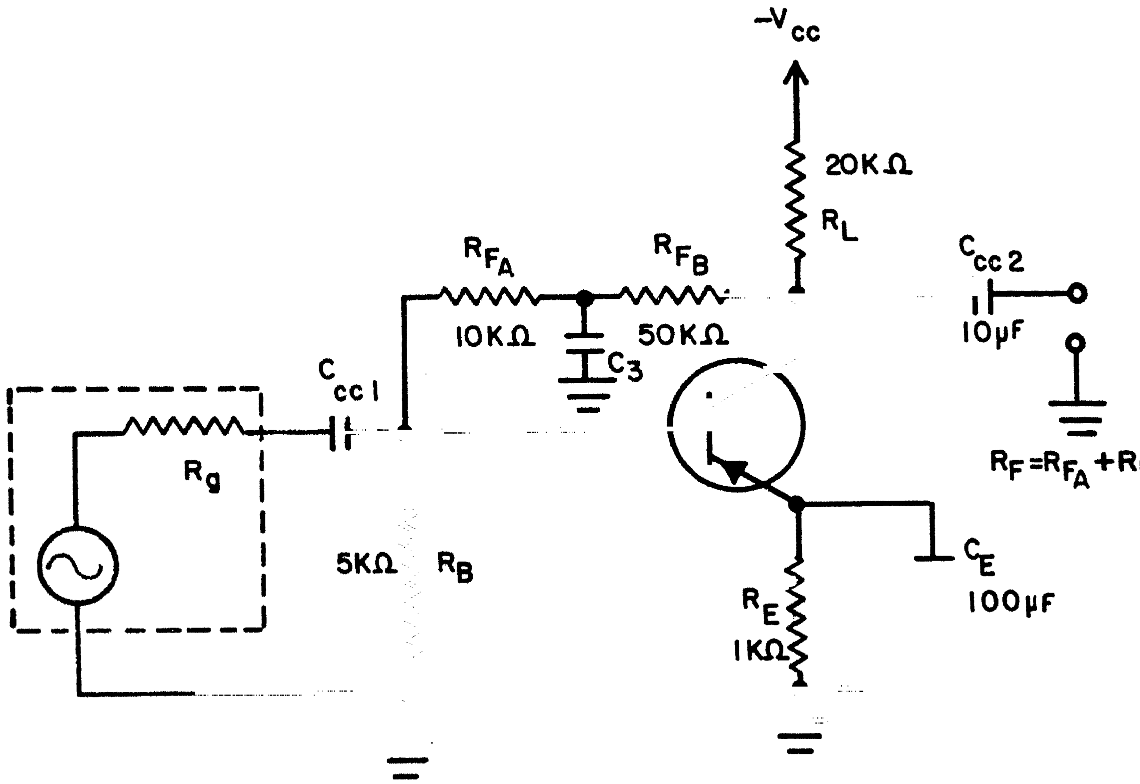
Figure 12

Voltage feedback is defined as that situation when the amount of signal fed back to the input (from the output) depends upon a voltage in the output circuit.

1. Whenever a voltage change occurs because of an I_{CO} variation, V_C will change and adjust the base voltage (V_{BB}) to correct for the change that caused it. R_E also develops d-c current feedback. The circuit provides a-c degeneration as well as d-c degeneration. The stability factor for figure 12 is:

$$S = \frac{\Delta I_C}{\Delta I_{CBO}} = \frac{(1+\beta)\{R_E(R_L+R_F+R_B)+R_BR_L+R_BR_F\}}{R_B+R_F+(1+\beta)\{R_E(R_L+R_F+R_B)+R_BR_L\}} \quad \text{(Eq 1.12)}$$

If greater gain is required, the circuit can be modified as in figure 13. The capacitor C_3 bypasses the a-c degeneration without altering the d-c circuit. $R_{FB} > R_{FA}$ because $R_{FB} || R_L$ and reduces the a-c load resistance.



Constant-Collector-Biased Common-Emitter Amplifier

Figure 13

i. These, are the stabilizing schemes and equations used on the common emitter. The choice between voltage and current-feedback is largely determined by the size of the d-c load resistance. If the d-c R_L is large, as usually the case for RC-coupled amplifiers, the voltage feedback (emitter at a-c and d-c ground) is as effective as the current type. For transformer coupling, where the d-c R_L is low, current feedback is much more effective than the other.

j. Although we have concentrated on the I_{CBO} variation the analysis, it should be remembered that h_{FE} and V may also need attention. Many of the same technicqu can be applied to the analysis of these two factors.

k. Two general procedures are available for incorporating the S in any design situation:

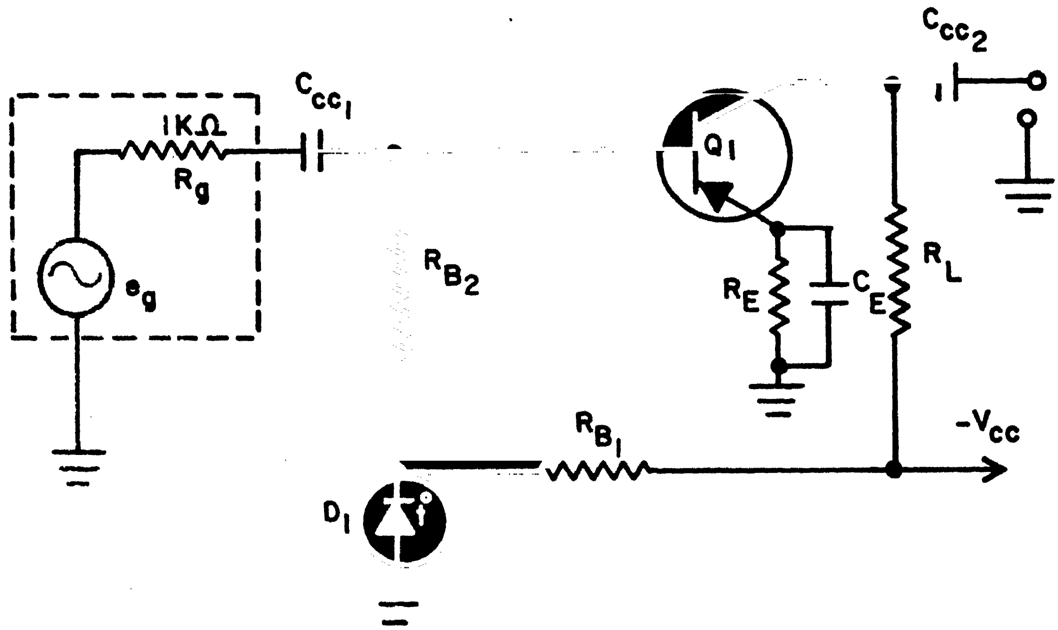
(1) Determine the appropriate S value and then use the various d-c equations to fix the circuit component values which will give the S.

(2) Decide upon the component values by the usual a-c considerations and then check the resulting S.

D. Additional Stabilizing Techniques

1. When using temperature-sensitive elements for stability, the idea is to cause the circuit conditions to change with temperature so that the changes effected by the transistor are compensated.

2. Figure 14 is an example using a diode (D_1) that has similar characteristics as the emitter-base junction of Q_1 (negative temperature coefficient). Any temperature variation would affect the base voltage and correct I_B to compensate for the change. Note also that current feedback is still used.



Temperature-Compensated Common-Emitter Amplifier

Figure 14

3. As was seen, a basic common-emitter amplifier may become somewhat complicated, as the stability is improved with added components.

E. Common-Base amplifier

1. The common-base amplifier has the following characteristic

   a. Capable of the highest voltage gain of the three basic configurations;

$$A_V \approx \alpha \left(\frac{R_o}{R_i}\right)$$

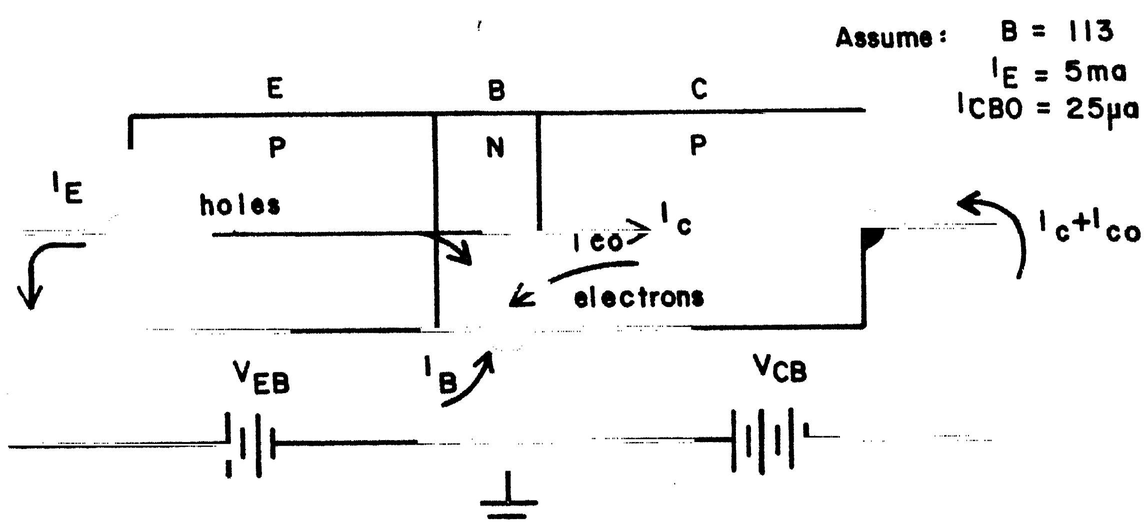
   b. A current gain called Alpha $= \frac{\Delta I_C}{\Delta I_E}$ always less than one.

   c. Very low input resistance; high output resistance.

   d. Used mainly where the matching of a low to a high resistance is required.

   e. Ideal stability factor in the basic circuit configuration.

2. Figure 15 will be used to illustrate the common-base amplifier, its current flow and direction of current flow



Current Flow in a PNP Transistor

Figure 15

Example 1:

$$\alpha = \frac{\beta}{1+B} = .99; \quad I_C = \alpha I_E$$

$$= (.99)(5mA)$$

$$= 4.95 \text{ mA}$$

$$I_B = I_E - I_C$$

$$= 5 \text{ ma} - 4.95\text{mA}$$

$$= 50 \ \mu A$$

The 4.95 mA collector current did not include the effect of I_{CO}.

Actually, $I_C = \alpha I_E + I_{CO}$

$$= (.99)(5{,}000 \ \mu A) + 25 \ \mu A = 4{,}975 \ \mu A$$

Therefore:

$$I_B = I_E (1 - \alpha) - I_{CO}$$

$$= 5{,}000 \ \mu A \ (1 - .99) - 25 \ \mu A$$

$$= 50 \ \mu A - 25 \ \mu A$$

$$= 25 \ \mu A$$

It should be clear that if I_{CO} decreases I_B by its increase; I_E will remain constant and I_C will change only by I_{CO}. This would be an ideal stbility factor.

a. A transistor using constant emitter current biasing is shown in figure 16.

$$V_{EB} = V_{EE} - I_E R_E = 6 - \{1mA \times 5.8k\} = + .2V \qquad \text{(Eq 1.13)}$$

$$V_C = V_{CC} - I_C R_L = V_{CC} - (\alpha I_E + I_{CO})(R_L) \qquad \text{(Eq 1.14)}$$

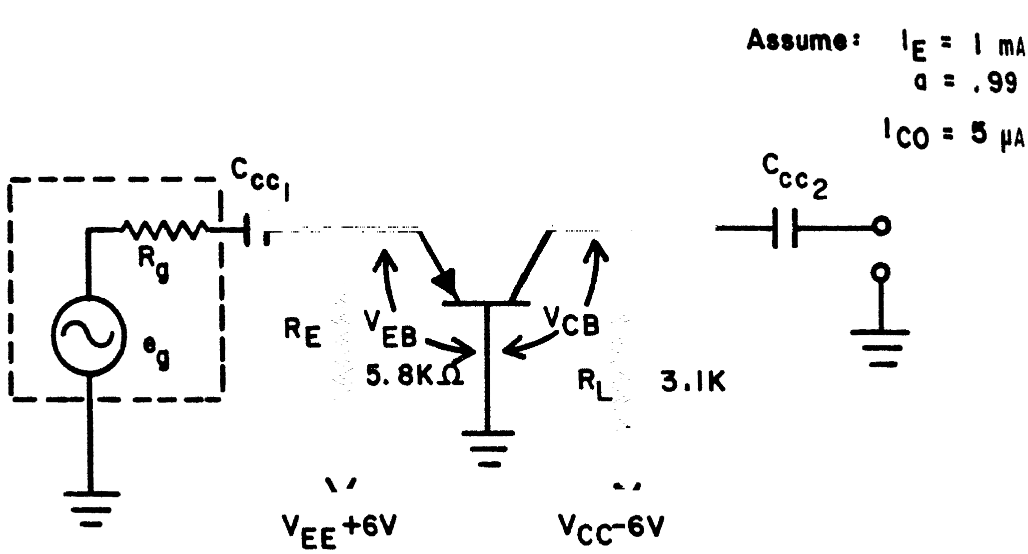
$$= -6 - \{(.99)(1000\mu A) + 5\mu A\}\{3.1k\}$$

$$\approx -3 \text{ volts}$$

$$V_{CB} = V_C - V_B \qquad \text{(Eq 1.15)}$$

$$= (-3)-(0)$$

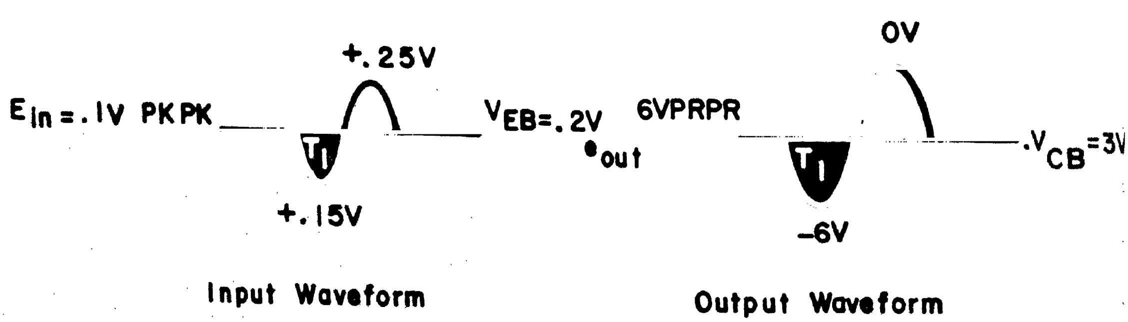
$$= -3 \text{ volts}$$



Constant Emitter Current Biased Common Base Amplifier

Figure 16

With the bias voltages computed, the amplifier is properly biased. Assuming a voltage gain of 60 and input signal of .1 volts p-p, the output signal is given in figure 17. The operating point is 3 volts (V_{CB}) and the maximum output without distortion is used.



Output Waveform Versus Input Waveform
Showing Phase Relationship

Figure 17

b. The stability of this circuit can be found with equation 1.11.

$$S = \frac{\Delta I_C}{\Delta I_{CBO}} = \frac{(R_B+R_E)(\beta+1)}{R_B + (\beta+1)R_E}\ ;\ R_B = 0:$$

$$S = \frac{R_E(\beta+1)}{R_E(\beta+1)} = 1;\ \text{ideal stability}$$

Any change in I_{CO} will change I_C by the same amount. Any current that becomes I_{CEO} simply aids the circuit in its stability. A disadvantage of this circuit is that it requires two power supplies. One power supply could be used with a voltage divider network; however, one must remember any resistance added in the base increases the stability factor.

F. Common-Collector Amplifier

1. The common-collector amplifier has the following characteristics:

   a. The highest current gain; $\gamma = \beta + 1$

   b. Voltage gain less than one; $A_V = \gamma\ (\frac{R_o}{R_i})$

   c. High input resistance; low output resistance.

   d. Used mostly for impedance matching.

   e. Good a-c and d-c stability due to its degenerative feedback.

A basic common-collector amplifier is shown in figure 18.

The bias voltages are as follows:

$$V_{BE} = V_{BB} - I_B R_B - I_E R_E \qquad \text{(Eq 1.16)}$$

$$= -4 - \{(27\text{x}10^{-6})(30\text{x}10^{3})\} - \{(101)(27\text{x}10^{-6})(1.1\text{x}10^{3})\}$$

$$\approx -.19 \text{ volt}$$

$$V_{CE} = V_{CC} - I_E R_E \qquad \text{(Eq 1.17)}$$

$$= -6 - \{(101)(27\text{x}10^{-6})(1.1\text{x}10^{3})\}$$

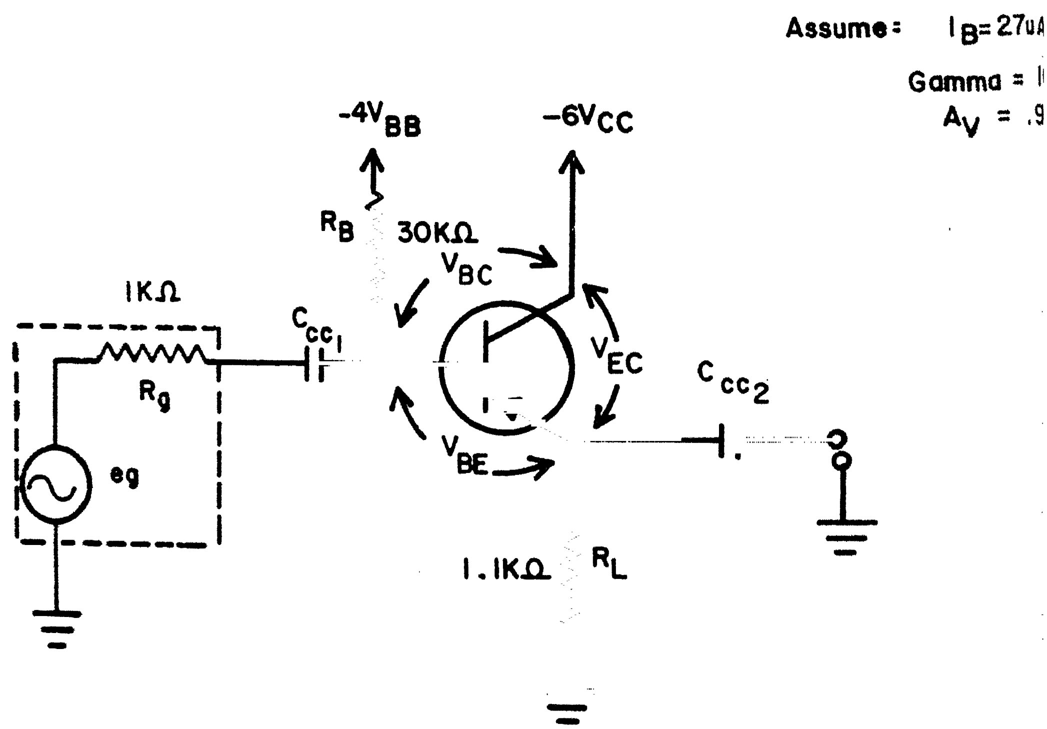
$$\approx -3 \text{ volts}$$

$$V_{BC} = V_{CC} - \{V_{BB} - E_{RB}\} \quad \text{(Eq 1.}$$

$$= -6 - \{4-(-.8)\}$$

$$= -6-(-3.2)$$

$$= -2.8 \text{ volts}$$

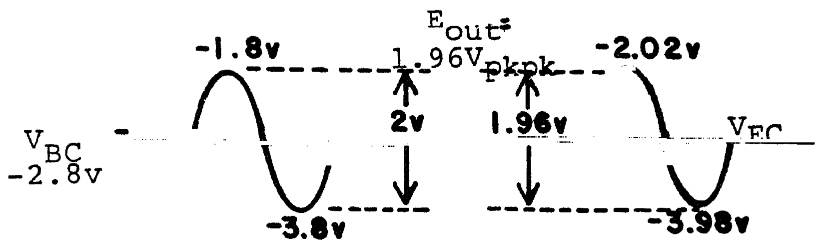


Basic Common-Collector Amplifier

Figure 18

If a 2V p-p signal was applied to the amplifier, the outp would be as shown in figure 19.

2. The S of this circuit is approximtely equal to the ratio R_B to R_L. Equation 1.9 could be used to analyze this circuit also. The common collector amplifier's d-c stability could be adjusted to a very low value if its input resistance was sacrificed. The choice of stability would be determined by the use of the circuit.

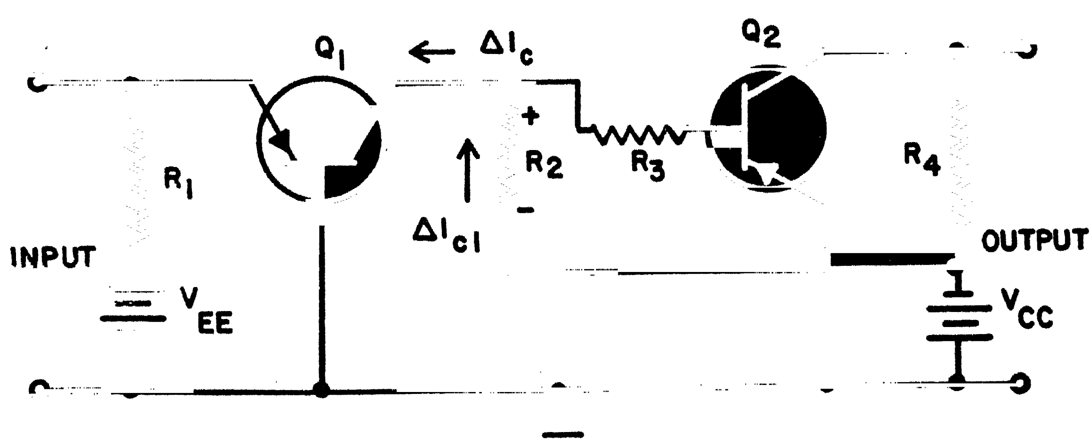


(a) INPUT WAVEFORM (b) OUTPUT WAVEFORM

Output Waveform Versus Input Waveform
Common-Collector Amplifier

Figure 19

G. D-c amplifier - Sometimes direct-coupled amplifiers are used to stabilize I_C variations. An example is given in figure 20. A d-c amplifier amplifies d-c voltage and very low frequency a-c signals. This circuit is arranged so that an increase in collector current caused by a temperature rise in transistor Q_1 will reduce the forward bias in transistor Q2. The voltage drop across resistor R_2 opposes the forward bias on Q_2. By selecting the values of resistors R_2 and R_3 so that the voltage drop across R_2 is the larger, the change in I_C of Q_1 will limit the tendency of transistor Q_2 collector current to increase with temperature.



Two-stage Temperature-Stabilized d-c Amplifier

Figure 20

H. Summary

1. These are but a few of the many schemes used to stabilize transistor amplifiers. The method used will be primarily determined by the requirements of the circuit and the environment it will operate in.

2. Items that should be remembered concerning biasing arrangements are:

   a. Reverse-bias collector current I_{CBO}, also called I_{CO}, increases rapidly at high temperatures and causes increased collector current.

   b. Emitter-base junction resistance decreases with increasing temperature and causes increased emitter current.

   c. The stability factor (S) is defined as the ratio of a change in collector current (Δ_{IC}) to a change in minority current (ΔI_{CBO}) and is expressed as:

   $$S = \frac{\Delta_{IC}}{\Delta I_{CBO}}$$

   d. An emitter swamping resistor minimizes variations in emitter current caused by variations in emitter-base junction resistance.

   e. Zero base resistance limits the accumulaton of majori carriers (I_{CO}) in the base region and therefore limit the.increase in emitter current due to this cause.

   f. The basic common-base amplifier (figure 16) exhibits best temperature stability because it uses an emitter swamping resistor and zero base resistance.

   g. The basic common-emitter amplifier (figure 6) exhibit poor temperature stability because it uses a base resistor and zero emitter resistance.

   h. The temperature stability of the basic common-collec amplifier (figure 18) depends upon the ratio of base resistance to emitter resistance.

   i. D-c negative voltage and current feedback (figure 12 can be used to minimize variations in collector curr with temperature.

   j. A forward-biased junction diode has a negative temperature coefficient of resistance.

   k. A reverse-biased junction diode has a negative temperature coefficient of resistance provided the reverse bias voltge does not equal or exceed BV_{CBO}.

NOTETAKING SHEET 2.8.1N

BIASING ARRANGEMENTS

REFERENCES:

1. Electronic Circuit Analysis, Vol. I, NAVAIR 00-80-T-79, Chapter 8.

2. Milton S. Kiver, Transistor and Integrated Electronics. New York, N.Y., McGraw-Hill Book Company, 1972, Fourth Edition.

NOTETAKING OUTLINE:

I. General Information - Biasing

II. Operational Analysis of the Common-Emitter Amplifier

A. Biasing

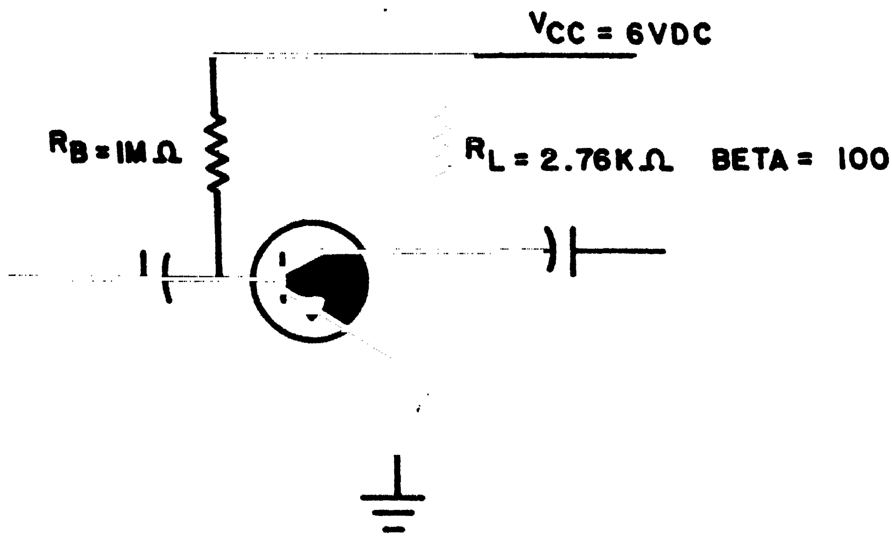


Figure 1

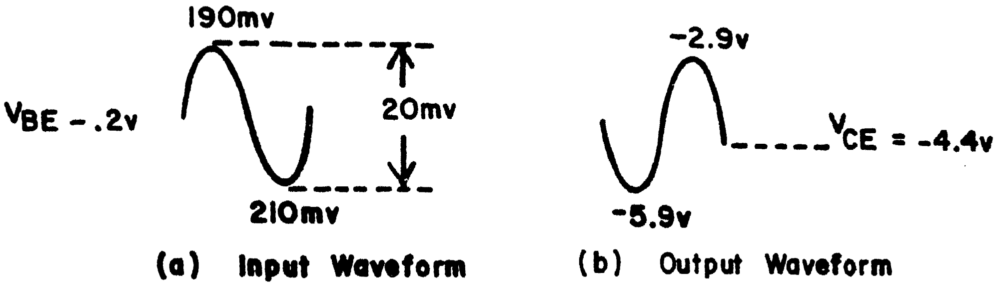


Figure 2

B. Temperature variations

C. Reversed bias collector Currect (I_{CBO})

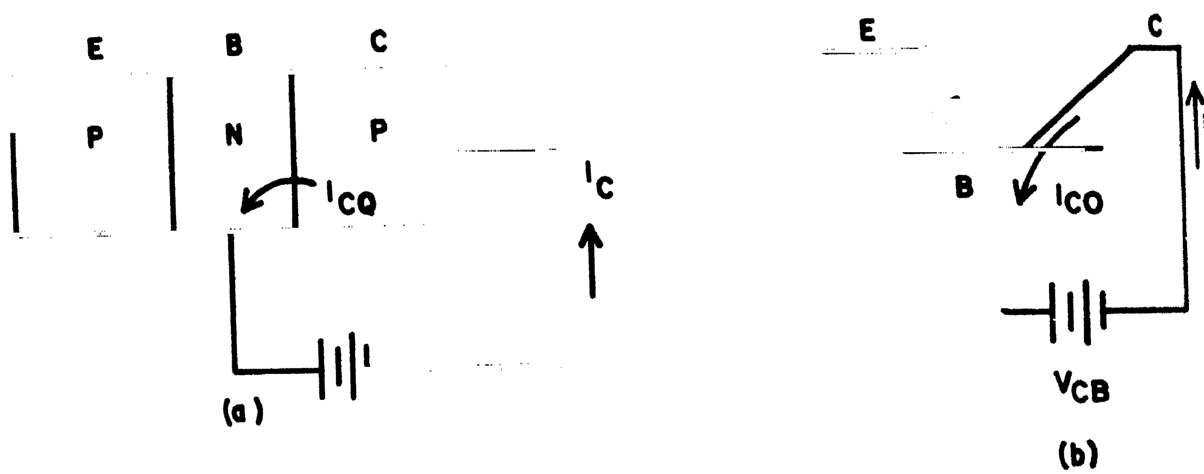


Figure 3

D. Beta

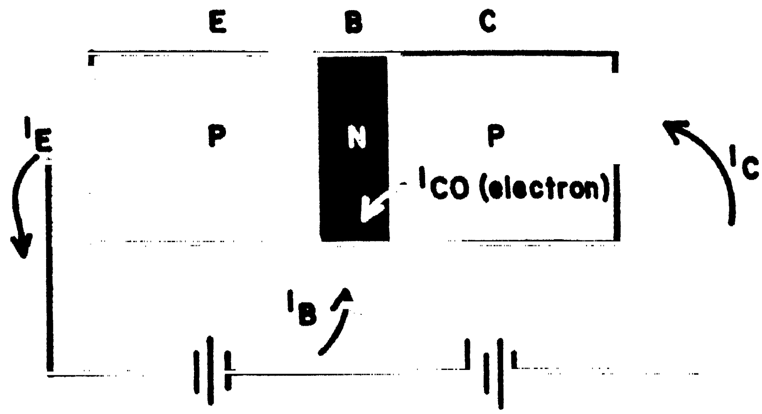


Figure 4

III. Stabilization of Common-Emitter Amplifier

A. Stability

B. Constant-emitter-current biased common-emitter amplifier

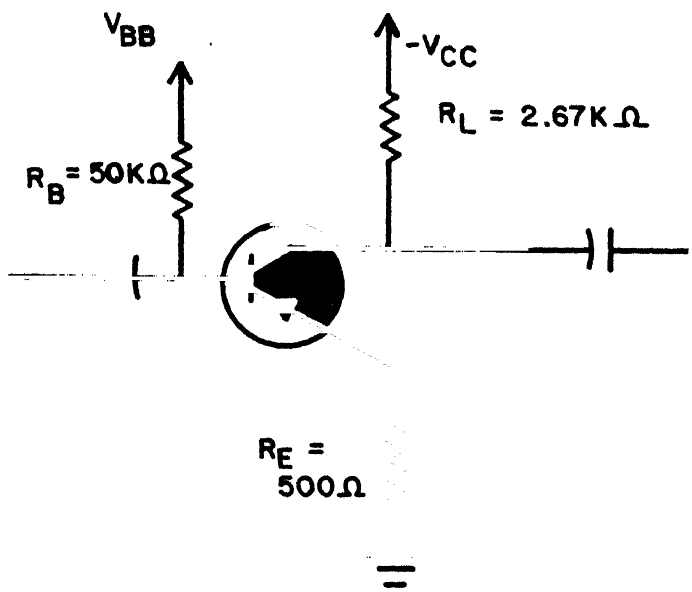


Figure 5

C. Constant-base-voltage biased common-emittr amplifier

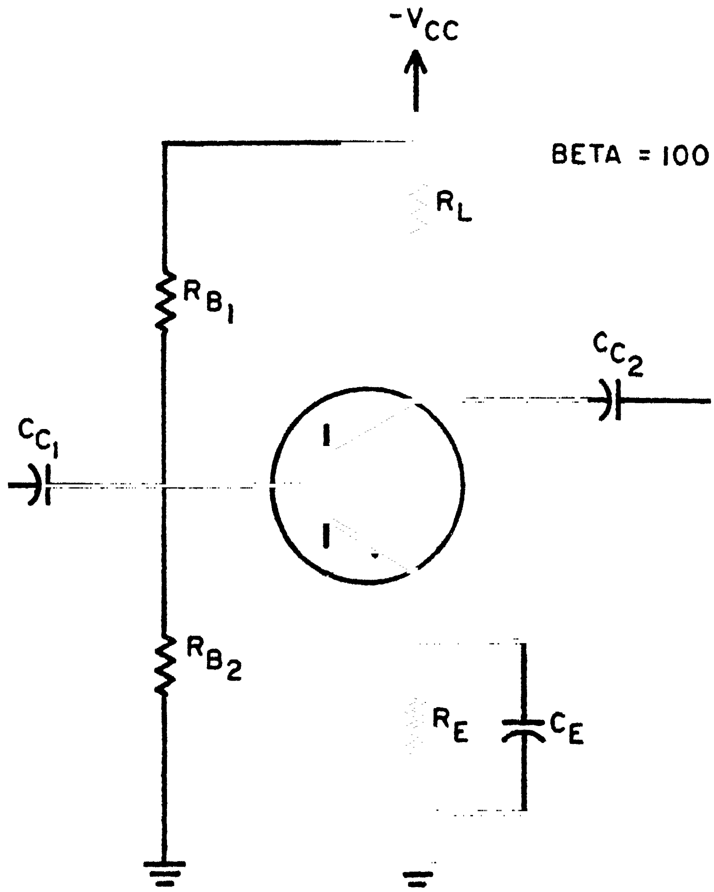


Figure 6

D. Constant-collector-voltage biased common-emitter amplifier

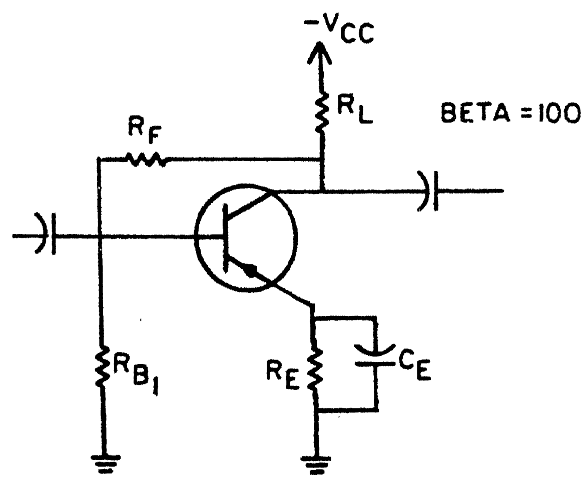
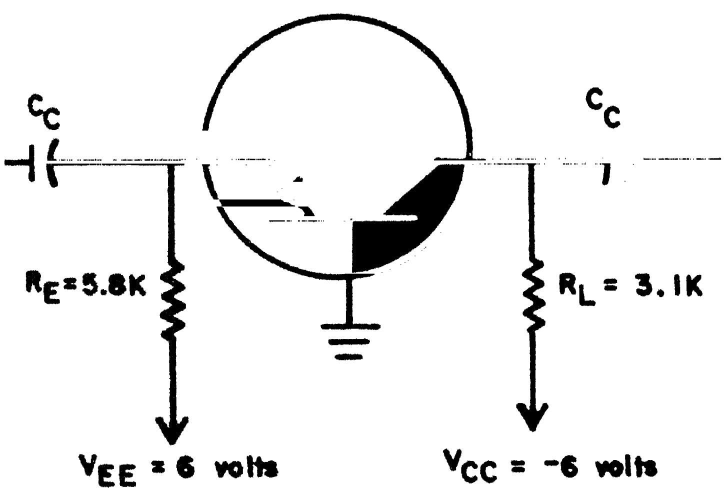


Figure 7

IV. Operational Analysis of the Common-Base Amplifier

A. Biasing



ASSUME: I_E = 1 mA
ALPHA = .99
I_{CO} = 5 uA

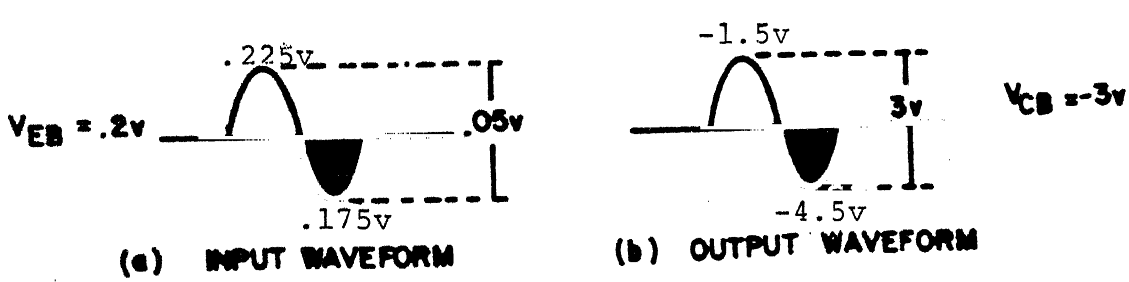


Figure 8

B. Stability

V. Operational Analysis of the Common-Collector Amplifier

A. Biasing

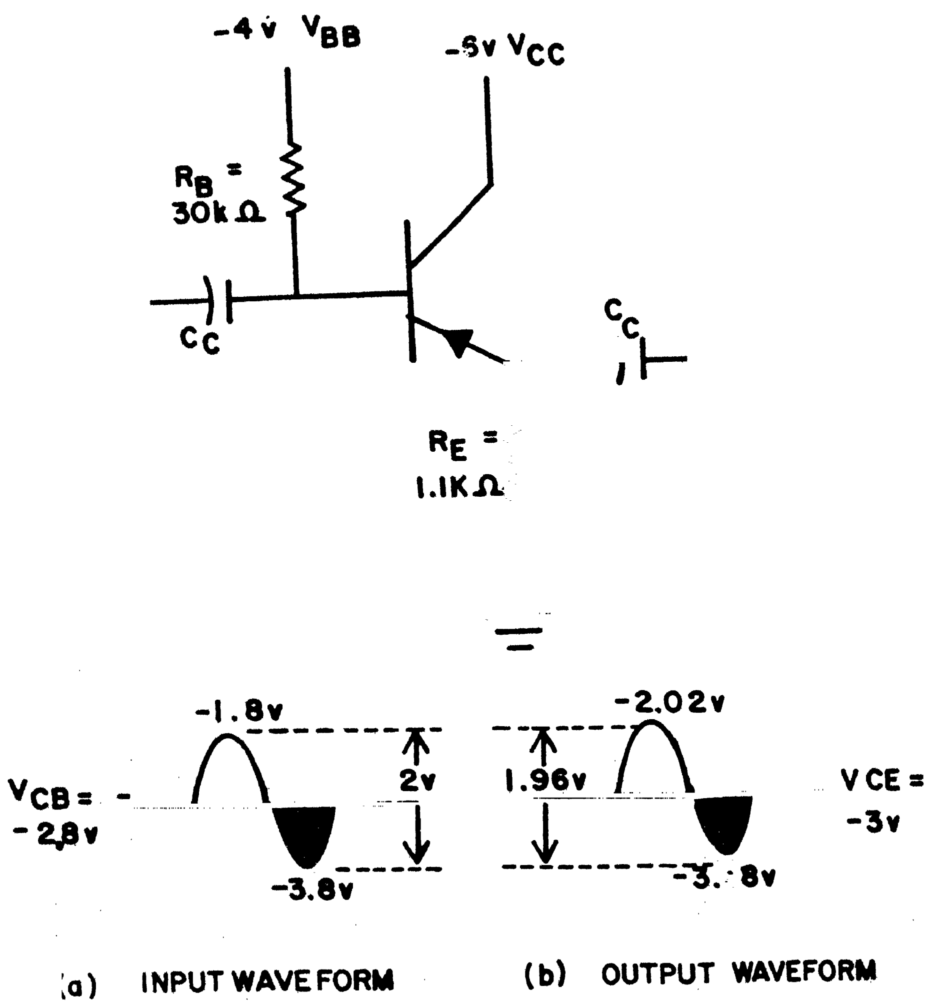


Figure 9

B. Stability

DATA SHEET 2.9.1D

BIASING ARRANGEMENTS
LABORATORY

INTRODUCTION

The purpose of the data sheet is for you to record the effects of temperature on a transistor's operating point. You will apply heat to a transistor, and you will measure and record the resulting effects on current with and without compensating circuit components.

1. Temperature effects

   a. Establishing operating conditions:

      (1) I_C = ______________

      (2) V_{BE} = ______________

      (3) VCE = ______________

      (4) Output wveform

      ----

      (5) ______________ V_{p-p}

      (6) I_C = __________

      (7) V_{CE} = _________

   b. Effects of increased temperature:

      (1) V_{BE} = ____________

      (1a) ΔV_{BE} = ___________

      (2) I_C = _____________

      (2a) ΔI_C = ____________

      (3) Output waveform

      ----

      (4) ____________ V_{p-p}

      (5) V_{CE} = ___________

      (6) ΔV_{CE} = __________

c. Questions

(1) How is I_C affected by temperature changes? Why?

(2) How is V_{BE} affected by temperature changes? Why?

(3) Does temperature affect fidelity? Explain.

(4) What would be the result of a transistor's being expose[d] to extreme heat for a prolonged period of time?

____

Instructor's initials __________

2. Reducing temperature instability with the addition of an emitt[er] resistor.

a. R_7 equals 10 kΩ

(1) I_C = __________

(2) I_C after heating = __________

(3) ΔI_C = __________

b. R_7 equals 100 kΩ

(1) I_C = __________

(2) I_C after heating = __________

(3) ΔI_C = __________

c. E_{out} = __________

d. E_{in} = __________

e. A_v = __________

f. Effect of emitter bypass capacitor

(1) E_{out} = __________

(2) E_{in} = __________

(3) A_v = __________

g. Questions

(1) Does the introduction of an emitter resistor improve transistor temperature stability? Why?

(2) Does the size of the emitter resistor affect transistor temperature stability? Explain.

(3) What is a disadvantage of using an emitter resistor?

(4) How can the above disadvantage be compensated for?

(5) Does the emitter bypass capacitor stabilize I_{CO}? Why?

Instructor's initials __________

. Effects of R_B and R_E on temperature stability and A_v.

a. I_C = __________

b. I_C after heat = __________

c. I_C = __________

d. E_{out} = __________

e. E_{in} = __________

f. A_v = __________

NOTE: I_C and A_V with changed components.

g. I_C with changed components = ____________

h. I_C after heat = __________

i. I_C = ____________

j. E_{out} = __________

k. E_{in} = ___________

l. A_V = ____________

m. Questions

(1) In terms of stability, what conclusion regarding the ratio of R_B to R_E can be drawn from this part of the experiment? Explain?

____

____

(2) Why is it desirable to have I_{CO} flow through the collector-base junction rather than both the collect-base and the emitter-base junction: Explain.

____

____

____

Instructor's initials ______

4. Constant collector-voltage feedback to improve stability.

a. Operation at ambient temperature:

(1) I_C = __________

(2) E_{out} = ________

(3) E_{in} = _________

(4) A_V = __________

(5) I_C with heat applied = __________

(6) ΔI_C = _________

(7) I_C with R2 removed = ______________

(8) E_{out} = ______________

(9) E_{in} = ______________

(10) A_v = ______________

(11) I_C with heat applied = ______________

(12) ΔI_C = ______________

b. Comparing constant-base voltage bias to constant-collector voltage bias, explain any difference in their effects on gain and stability.

____

____

____

Instructor's initials ________

NOTETAKING SHEET 2.10.1N

DECIBELS

REFERENCES:

1. Cooke and Adams, Basic Mathematics for Electronics. New York: McGraw-Hill Book Company, Ind., Third Edition, Chapters 34 and 35.

2. Basic Electronics, Volume 1. NAVPERS 10087-C. Washington, D.C.: United States Government Printing Office, 1979, Chapter 11, pages 221-231.

NOTETAKING OUTLINE:

I. Review of Logarithms.

II. Decibels

III. Waveform Analysis

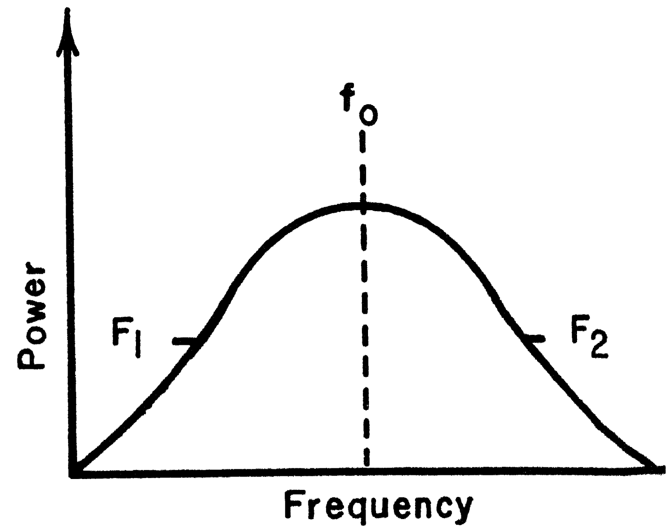


Figure 1 Bandwidth Curve

Table 1. Common Logarithms

COMMON LOGARITHMS

N	0	1	2	3	4	5	6	7	8	9
0	....	0000	3010	4771	6021	6990	7782	8451	9031	9542
1	0000	0414	0792	1139	1461	1761	2041	2304	2553	2788
2	3010	3222	3424	3617	3802	3979	4150	4314	4472	4624
3	4771	4914	5051	5185	5315	5441	5563	5682	5798	5911
4	6021	6128	6232	6335	6435	6532	6628	6721	6812	6902
5	6990	7076	7160	7243	7324	7404	7482	7559	7634	7709
6	7782	7853	7924	7993	8062	8129	8195	8261	8325	8388
7	8451	8513	8573	8633	8692	8751	8808	8865	8921	8976
8	9031	9085	9138	9191	9243	9294	9345	9395	9445	9494
9	9542	9590	9638	9685	9731	9777	9823	9868	9912	9956
10	0000	0043	0086	0128	0170	0212	0253	0294	0334	0374
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529
18	2553	2577	2601	2625	2648	2672	2695	2718	2742	2765
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067
N	0	1	2	3	4	5	6	7	8	9

N	0	1	2	3	4	5	6	7	8	9
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067
51	7076	7064	7093	7101	7110	7118	7126	7135	7143	7152
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987
63	7993	8000	8007	8014	8021	8028	8035	8041	8046	8055
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627
73	8633	8639	8645	8651	8657	8663	8669	8675	8661	8686
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996
100	0000	0004	0009	0013	0017	0022	0026	0030	0035	0039
N	0	[illegible]	2	3	4	5	6	7	8	9

INFORMATION SHEET 2.11.1I

FEEDBACK AMPLIFIERS

INTRODUCTION

There are several types of feedback circuits; each is determined by the nature of the signal that is fed back and the manner in which it is applied to the input circuit. The feedback signal can be proportional to the load current or to the load voltage. To investigate the various effects on circuits, we will use the block diagrams and the basic diagrams of various schematics. Further simplification is obtained by omitting all components that are bypassed, and the d-c biasing circuits.

REFERENCES

1. Slurzberg and Osterheld, Essentials of Radio-Electronics, Second Edition, McGraw-Hill Book Company, Inc., 1961.

2. Electronic Circuits, NAVSHIPS 0967-000-0120, March 1980.

INFORMATION SHEET 2.11.1I

FEEDBACK AMPLIFIERS

INTRODUCTION

There are several types of feedback circuits; each is determined by the nature of the signal that is fed back and the manner in which it is applied to the input circuit. The feedback signal can be proportional to the load current or to the load voltage. To investigate the various effects on circuits, we will use the block diagrams and the basic diagrams of various schematics. Further simplification is obtained by omitting all components that are bypassed, and the d-c biasing circuits.

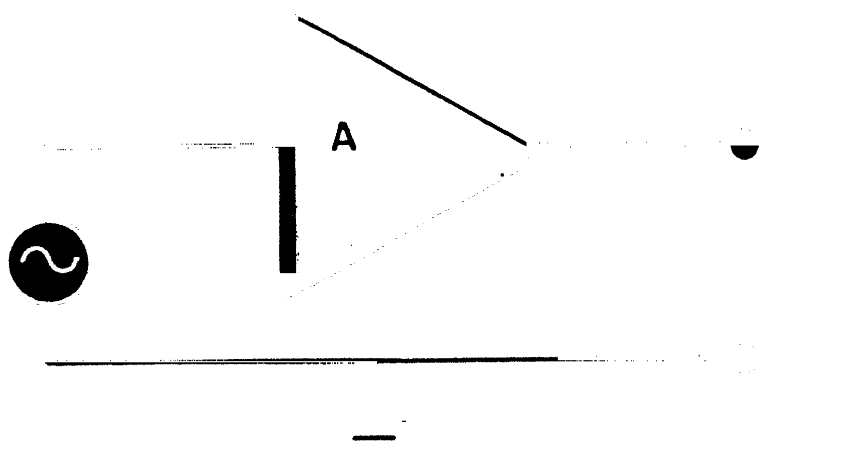
REFERENCES

1. Slurzberg and Osterheld, Essentials of Radio-Electronics, Second Edition, McGraw-Hill Book Company, Inc., 1961.

2. Electronic Circuits, NAVSHIPS 0967-000-0120, March 1980.

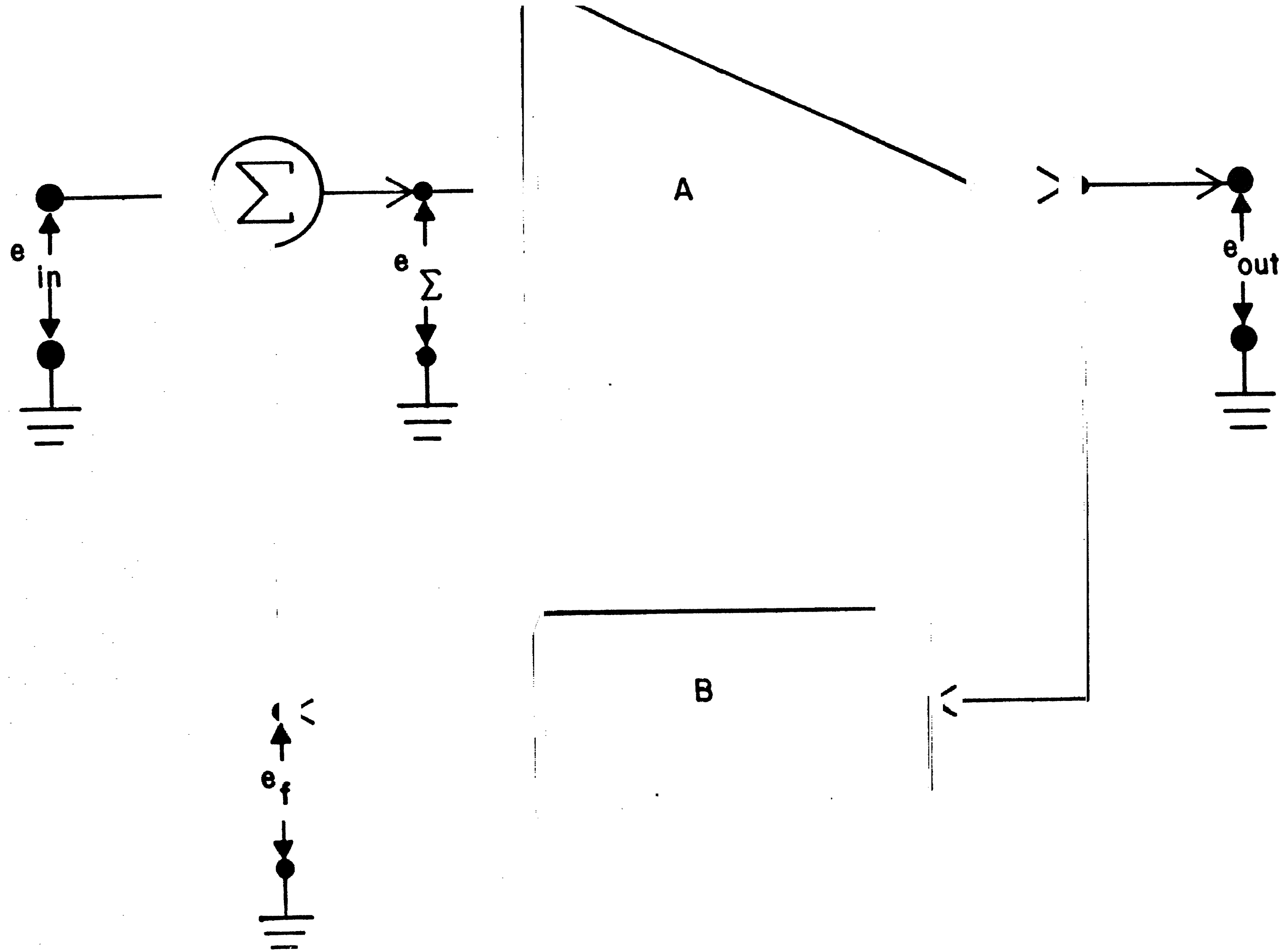
INFORMATION

I. The following figures are labeled to assist you in following the instructor through the lesson:



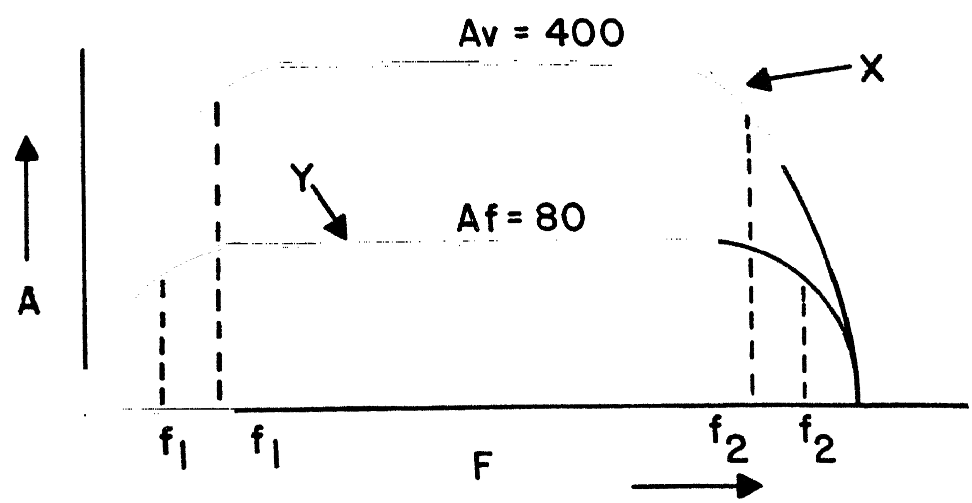
Open-Loop System

Figure 1

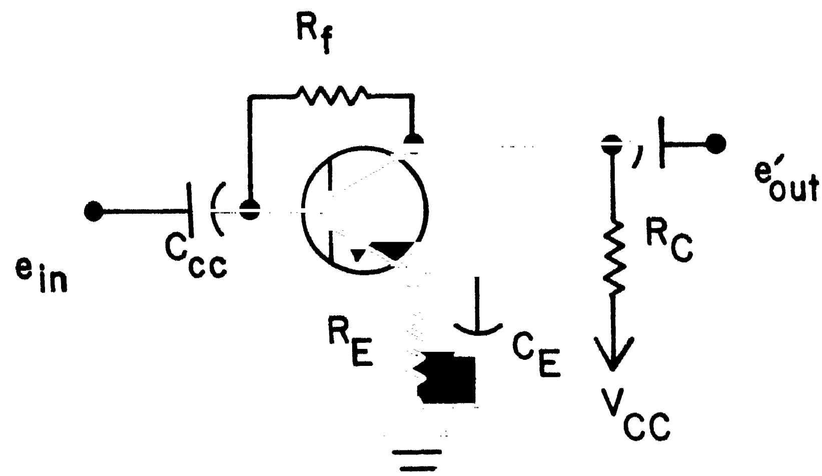


Closed-Loop System

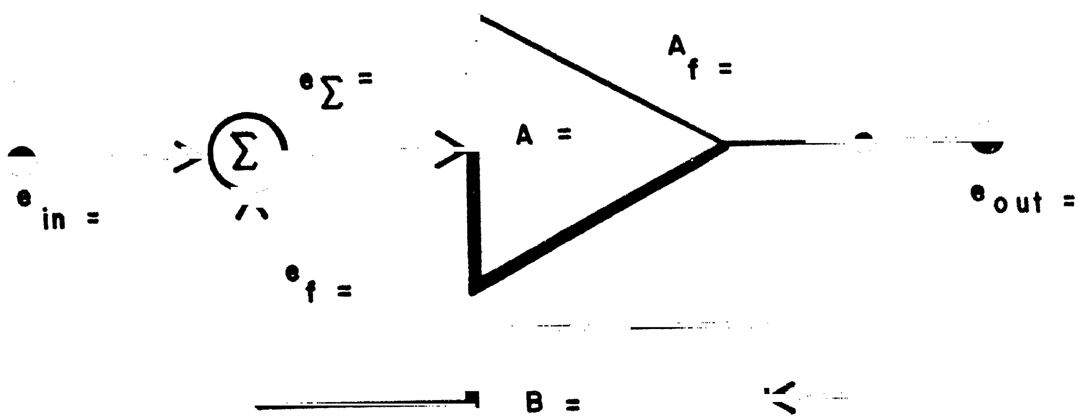
Figure 2



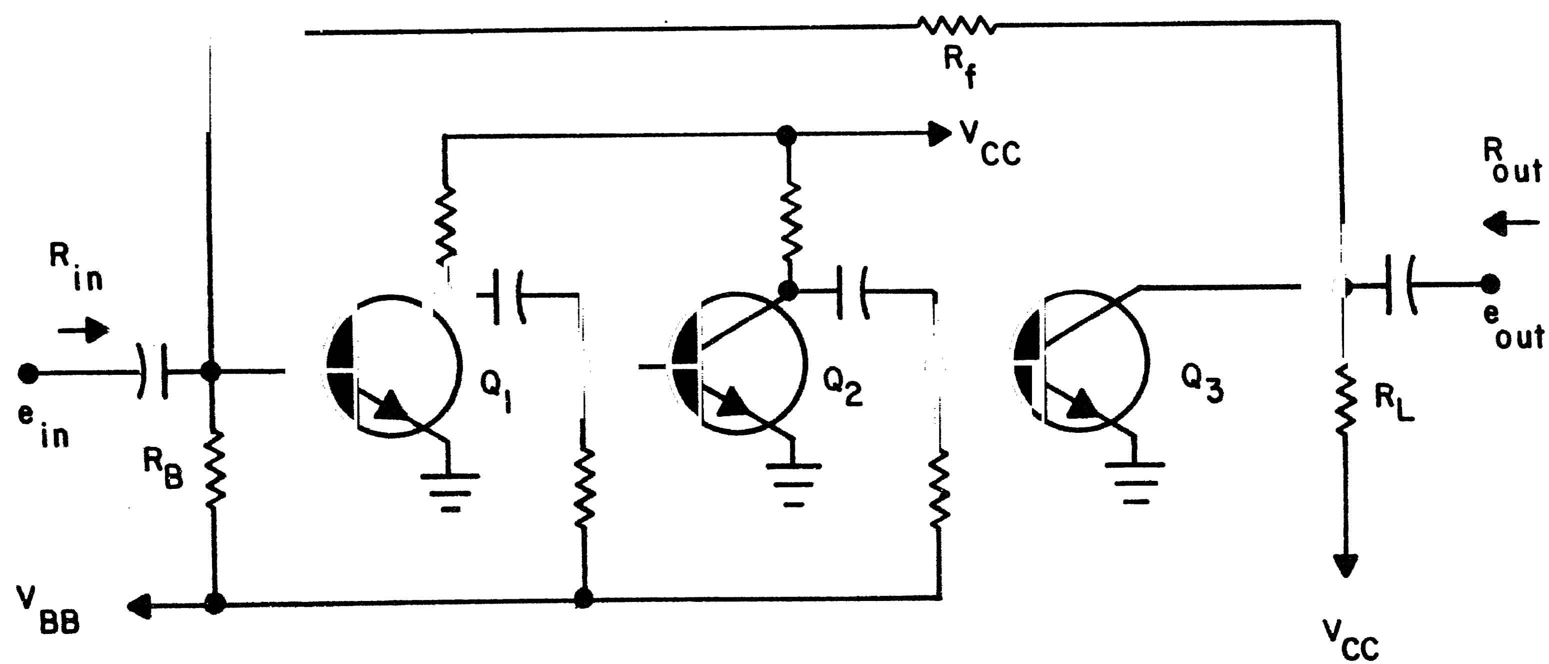
Frequency Response
Figure 3



Voltage Feedback
Figure 4

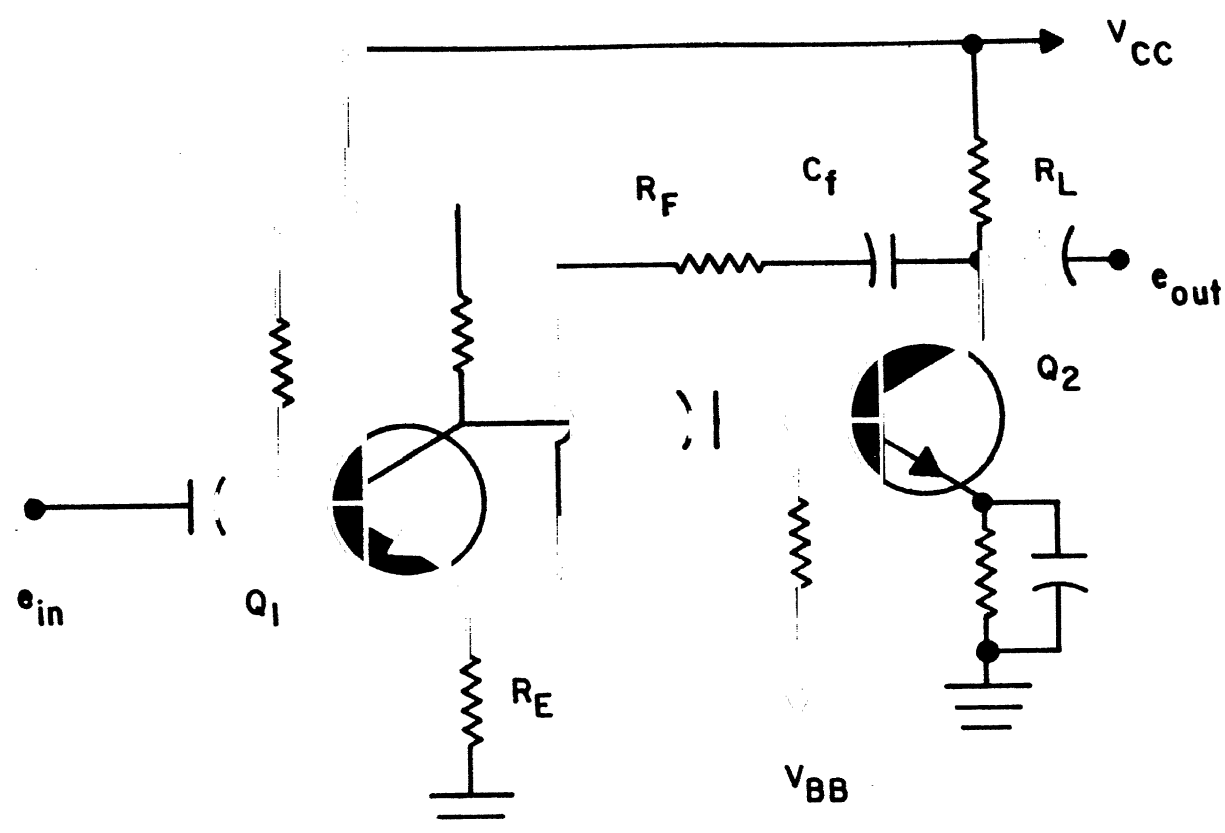


Simple Gain Problem
Figure 5



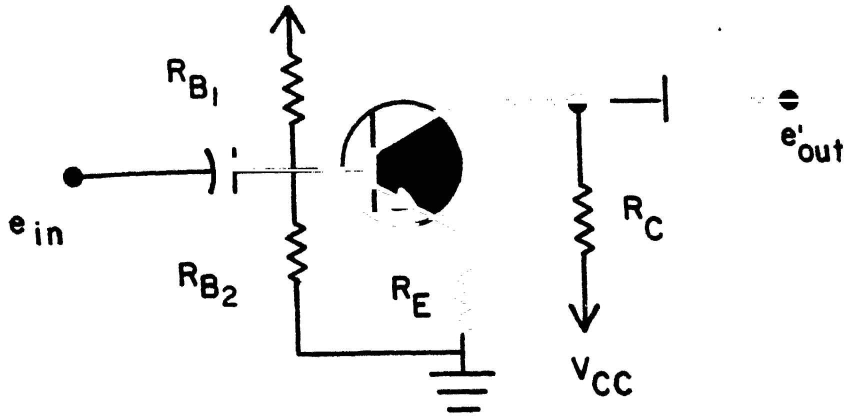
Multi-Stage Shunt-Voltage-Feedback Amplifier

Figure 6



Multi-Stage Shunt-Voltage-Feedback Amplifier

Figure 7



Current Feedback
Figure 8

II. Basic Gain Formula

A. Open-loop system implies that no feedback path exists between the input/output terminals. The drive to the gain-block (figure 1) is caused by e_{in} alone and not by any portion derived from e_{out}.

The basic gain formula is $A_V = \frac{e_{out}}{e_{in}}$. Therefore, $e_{out} = e_{in}A_V$.

Any change in A_V, causes a variation in e_{out}.

B. Closed-loop system implies there is some form of feedback from the output back to the input. It is used to overcome the sensitivity of e_{out} to variation in A_V. The principle of the closed-loop system is based on error detection. β represents a gain (or loss) factor introduced into e'_{out} before it emerges as e_f (the feedback voltage) where e'_{out} is the output signal with feedback applied. β is indicated in decimal form and may be -or + to indicate whether it will be degenerative or regenerative. This will cause e_f to add to or subtract from e_{in}. Σ is the symbol of the error detector. It will aid in developing e_Σ which is the algebraic sum of e_{in} and e_f. $e_\Sigma = e_{in} + e_f$, where $e_f = \beta e'_{out}$. The output will follow the input quite closely in the closed-loop system. The drive to the gain block is varied in such a manner as to hold e'_{out} relatively constant for changes in $A_V(\Delta A_V)$. Feedback may be defined as the process of causing a portion of the amplifier's output to be superimposed on its input. The block diagram in figure 2 will aid in developing the feedback equation.

C. $e'_{out} = A_v e_\Sigma$: e'_{out} is the output signal with feedback applied

$e_\Sigma = e_{in} + e_f$

$e_f = \beta e'_{out}$: by substitution,

$e_\Sigma = e_{in} + \beta e'_{out}$

therefore, $e'_{out} = A_v(e_{in} + \beta e'_{out})$. Multiplying through by A_v,

$e'_{out} = A_v e_{in} + A_v \beta e'_{out}$ to collect terms,

$-A_v e_{in} = -e'_{out} + A_v \beta e'_{out}$ or, as is commonly written,

$A_v e_{in} = e'_{out} - A_v \beta e'_{out}$, and

$A_v e_{in} = e'_{out}(1 - A_v \beta)$, dividing,

$$e'_{out} = \frac{A_v e_{in}}{1 - A_v \beta}$$

The closed loop gain (with feedback) is A_f.

$A_f = \dfrac{e'_{out}}{e_{in}}$ or as has been resolved previously,

$A_f = \dfrac{A_v e_{in}}{1 - A_v \beta} \div e_{in}$ which could be rewritten as

$A_f = \dfrac{A_v}{1 - A_v \beta}$ = closed-loop gain.

III. Negative Feedback Amplifiers

A. General

1. There are several types of feedback circuits; each i determined by the nature of the signal that is fed b and the manner in which it is applied to the input circuit. Thus the feedback signal can be proportior to the load current or to the load voltage.

2. The signal fed back can be applied in series or in shunt with the input circuit. It, therefore, follo that there are four basic types of feedback circuit and they are:

a. The voltage output-shunt input.
b. The voltage output-series input.
c. The current output-shunt input.
d. The current output-series input.

3. The input and output impedances of these four types of feedback circuits are affected differently by the applied feedback, but their individual gains will be affected similarly by the applied feedback.

4. To investigate these effects, we will use the block diagram form and basic schematic diagrams. The blocks will contain both the signal input and output leads, plus the common input and output leads for clarification. The assumptions made are that the basic amplifier is unilateral; that is, there is no interaction between its input and output terminal pairs and the input/output impedance of the feedback network is sufficiently high to ensure that it does not load the basic amplifier.

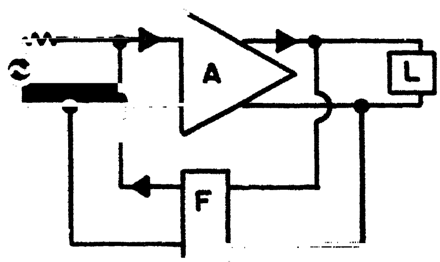
5. Further, simplification is obtained by omitting all components that are bypassed, those capacitors with negligible reactance at mid-frequencies, and the d-c biasing circuits. The signal generator is always displayed along with its internal resistance.

B. Voltage output-shunt input

1. Figure 9a shows the feedback block, "F", across the load and the input. Any change in voltage across the load is sampled and a portion of this sample is applied across, or in shunt with the input terminals. Note, in the following sections of figure 9, the feedback resistor is in series with the input resistance of the first stage.

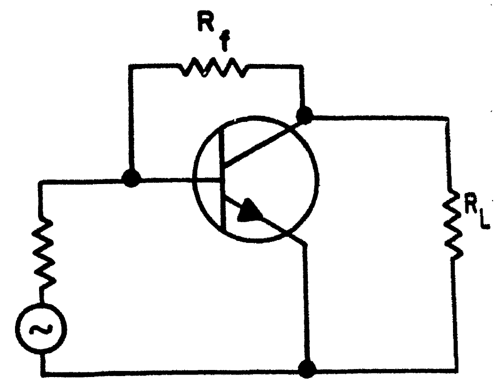
2. If the feedback block is in shunt with both the input/output terminals of the gain-block, then the input/output resistance must be lower with this type of feedback. Also, the polarity difference between the input signal and feedback signal is 180°. The gain-block resembles a constant-voltage source and is rendered insensitive to device parameter changes, relative to the amount of feedback applied.

3. In the schematics shown, blocking capacitors would isolate the d-c voltages from upsetting the bias levels. However, with careful design, the bias levels can be set so that direct coupling can be used and the gain-block is compensated for drift (drift caused by changes in ambient temperature). Also, various reactances can be placed in series and/or parallel with the feedback resistors to shape properly the gain-bandwidth contour, referred to as frequency compensation or equalization.

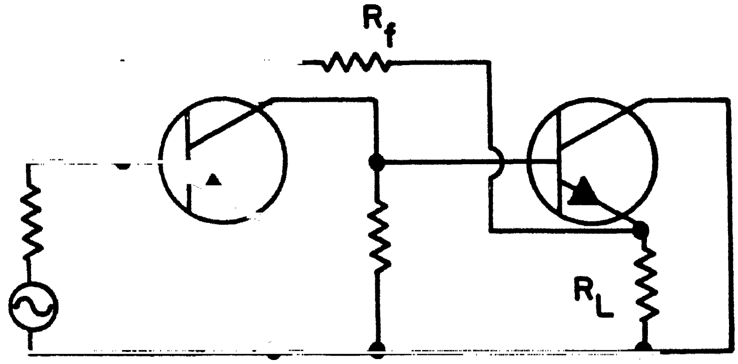


Voltage output-shunt input

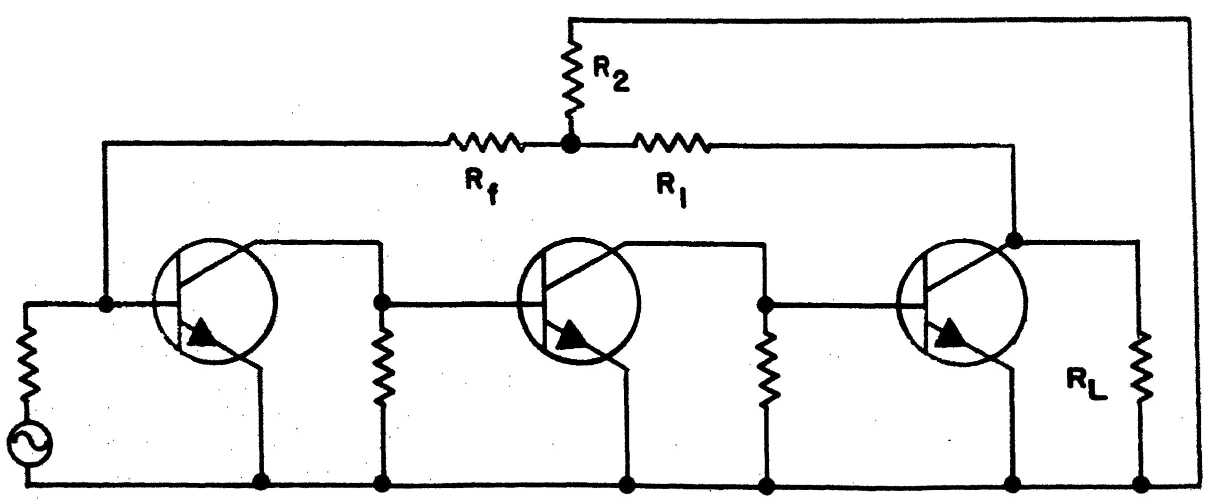
(a)



(b)



(c)



(d)

Figure 9

4. Figure 9b represents a single stage with local feedback applied. Figure 9c is a CE to CC configuration, with the output resistance extremely low. Figure 9d shows three stages of CE amplifiers. The load for the output stage is R_L. R_1 and R_2, in series, are in parallel with R_L, and the portion of the output voltage at their junction is fed back through R_f, which is in series with the R_i of the first stage.

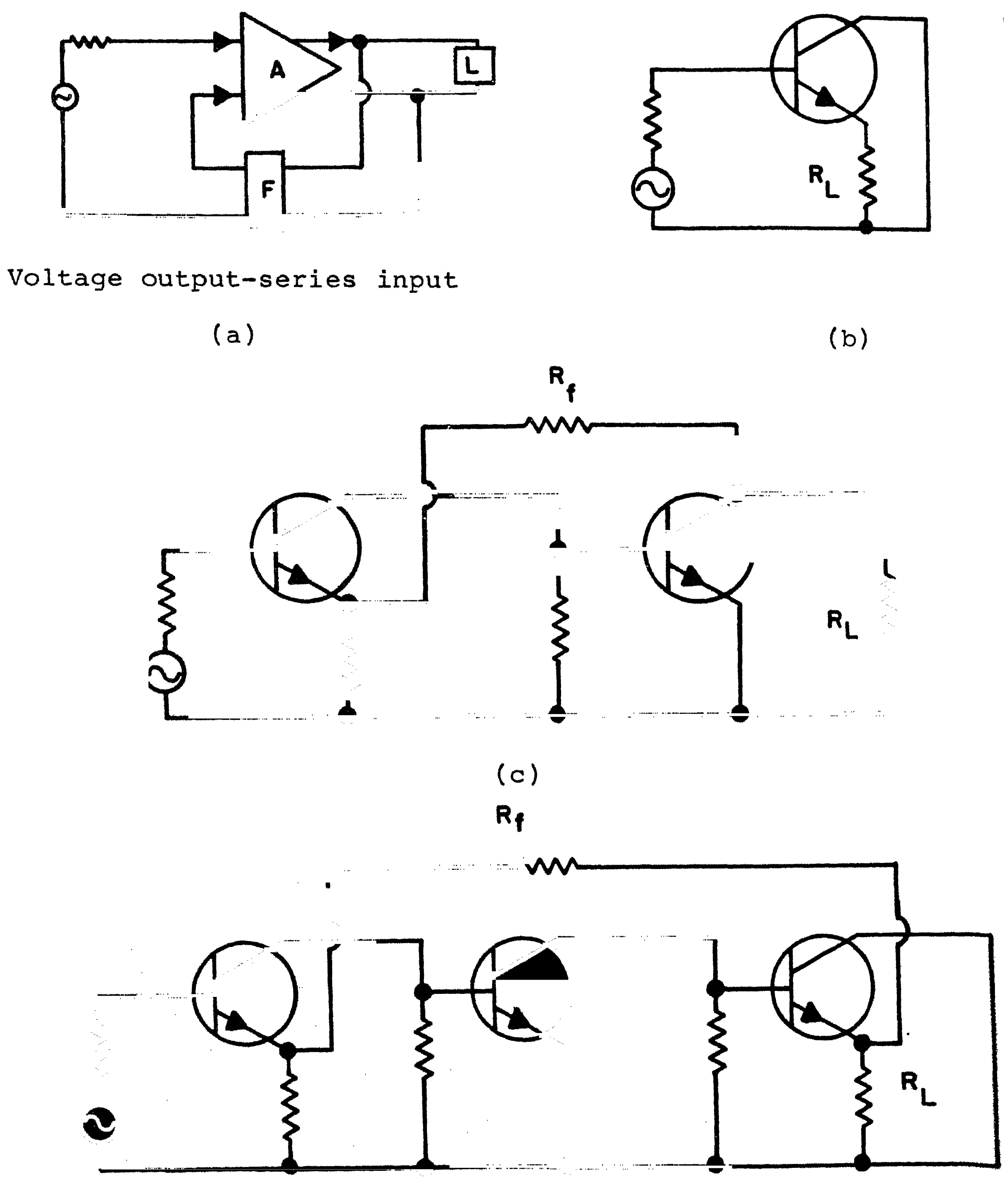
5. In all the cited cases, the input driving signal has been effectively reduced, reducing the output signal. Both the input and output resistances are lowered. Bandwidth is increased, distortion reduced, stability increased, and periodic noise reduced.

C. Voltage output-series input

1. Figure 10a is the block diagram of this feedback arrangement. The voltage across the load is sampled and a portion of it, called the feedback voltage, is applied in series with the input signal. The polarity of the feedback signal is such that it will oppose the input signal, reducing the effective drive to the gain-block.

2. Figure 10b shows the extreme case of 100% voltage feedback in an emitter follower or CC amplifier. Reasoning reveals that this could not be 100% degeneration, or else there would be no output. The only way to cause 100% degeneration would be to throw the power "on/off" switch to the "off" position.

3. Figure 10c shows two CE amplifiers and figure 10d has an added CC stage to effect a much lower output resistance. In all cases shown so far, the output circuits are shunted by the feedback circuits, lowering the output resistances and keeping the output signals constant, with variations in the gain-block. However, in figure 10, the feedback voltage is applied in series with the input signal, thus greatly reducing the input driving signal current. This has the effect of increasing the input resistance. The polarity of the feedback signal is in phase with the input signal and opposes its action. Therefore, the input resistance is increased while the output resistance is lowered. With this application of feedback, the gain, distortion, noise, and stability are affected the same as with figure 9.



Voltage output-series input

(a)

(b)

(c)

(d)

Figure 10

D. Current output-shunt input

1. Figure 11a shows the block diagram with the output current flowing through the feedback sampling circuit. The feedback voltage developed is applied in shunt with the input signal, the polarities being 180° out-of-phase, to reduce effectively the driving signal to the gain-block.

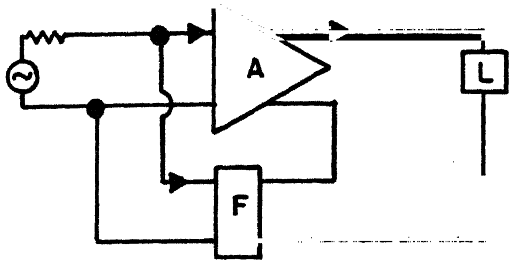
2. Figure 11b shows a CE to CE amplifier with the output resistance being increased and the input resistance being lowered by this type of feedback. The feedback signal is taken from R_1, which samples the output load current. It is then applied through R_f in series with the R_i of the first stage. Since this type of feedback tends to keep the output current constant, the gain-block resembles a constant-current generator with its high output resistance.

3. In figure 11c, R_2 samples the load current and is also a part of the load resistance of the last stage. Load-current variations develop the feedback signal voltage across R_1. The gain, stability, distortion, and noise of this type of feedback application are similar to the others discussed.

E. Current output-series input

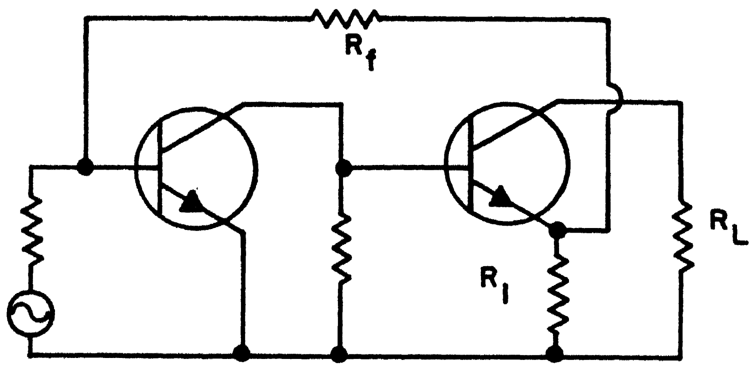
1. Figure 12a shows a block diagram with the output load current flowing through the feedback sampling circuit, and the feedback voltage developed by the load current, which is applied in series with the input signal.

2. This application maintains a constant output current and greatly controls the input driving signal current. The input and output resistances are increased by this type of feedback application. Figure 12b shows the CE amplifier with the resistor in the emitter leg. It is strongly emphasized here that this resistor will prevent thermal runaway. Reasoning reveals that if the output current tends to "run", the feedback voltage it develops across R reduces the forward bias, resulting in slowing the "run" to a "crawl" and a "stand still." This resistor, when bypassed, allows maximum stage gain. However, when unbypassed, it introduces degenerative feed-back to the applied a-c signal and improves the stability, bandwidth, distortion, and noise figure as discussed previously.

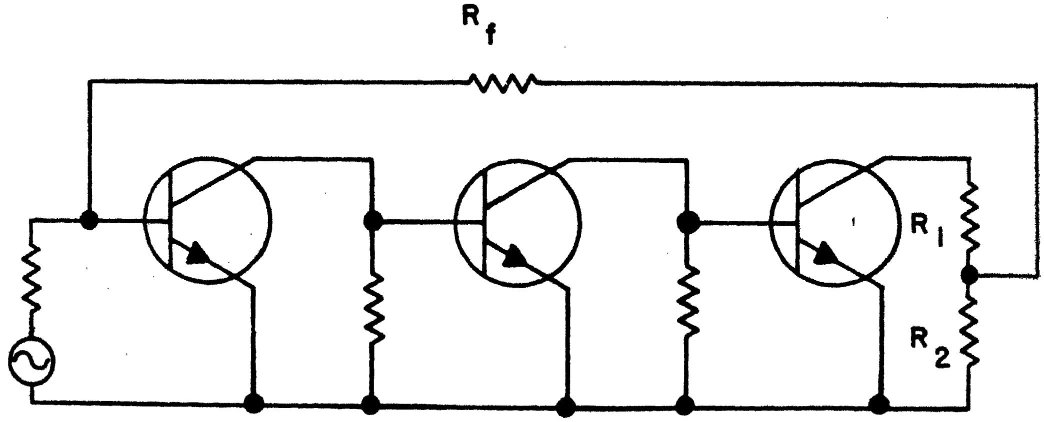


Current output-shunt input

(a)



(b)



(c)

Figure 11

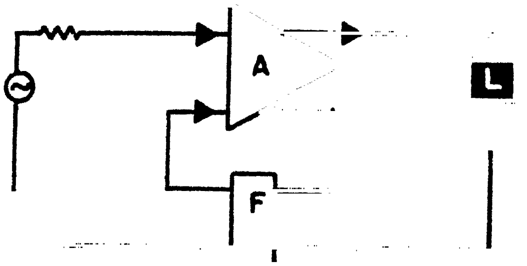
3. Figure 12c is a very popular compound-connection configuration. R_1 develops the feedback signal caused by load-current variations. The output stage is also the emitter load for the input stage. The input resistance is extremely high, along with the corresponding increase in output resistance. Figure 12d shows three CE amplifiers with applied feedback (current output-series input).

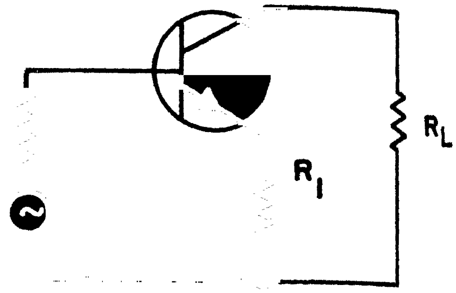
F. Combinational feedback

1. Depending on the requirements, feedback can alter slightly or drastically, the input/output resistance of any type of amplifier. The characteristics of one can be overshadowed by another, depending on the amount of each applied.

2. Figure 10c is voltage output-series input, but the emitter of the first stage introduces a small amount of current output-series input, locally. This, of course, is unavoidable, because the emitter of the first stage must be above ground for injection of the overall feedback loop. The same holds true for figure 10d.

3. The complexities which reactive components add to feedback are too great to be analyzed in this allotted time. The technician will see various types and applicatons during his troubleshooting procedures. With experience and further studies, you will become familiar with the forever common feedback circuits.

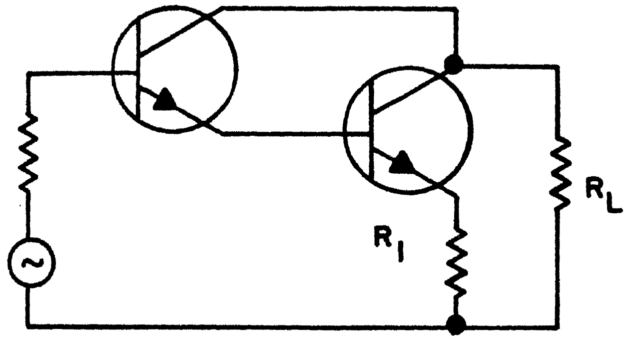




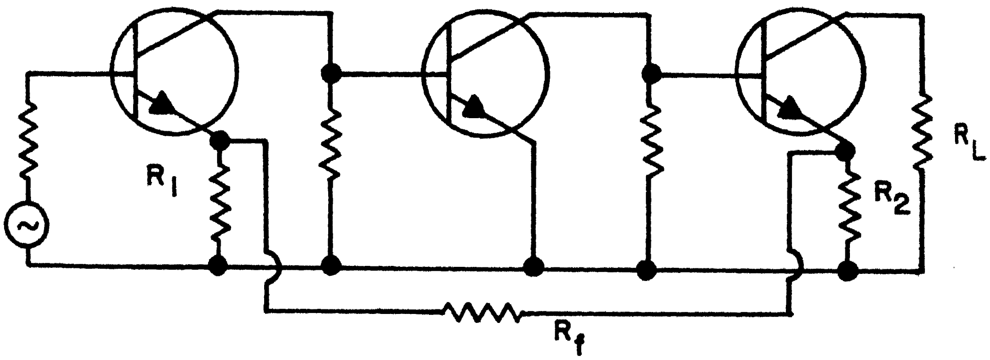
Current output-series input

(a)

(b)



(c)



(d)

Figure 12

NOTETAKING SHEET 2.11.1N

FEEDBACK AMPLIFIERS

REFERENCES:

1. Essentials of Radio-Electronics, Slurzburg & Osterheld, McGraw-Hill Co., Second Edition, 1961.

2. Electronic Circuits, NAVSHIPS 0967-000-0120, March 1980.

NOTETAKING OUTLINE:

I. The Open-Loop System

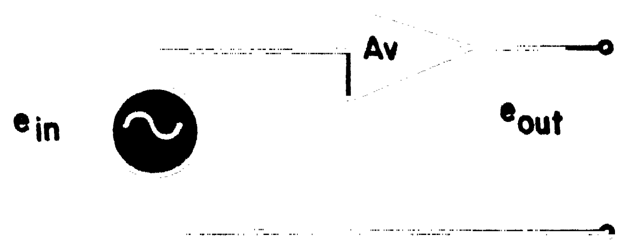
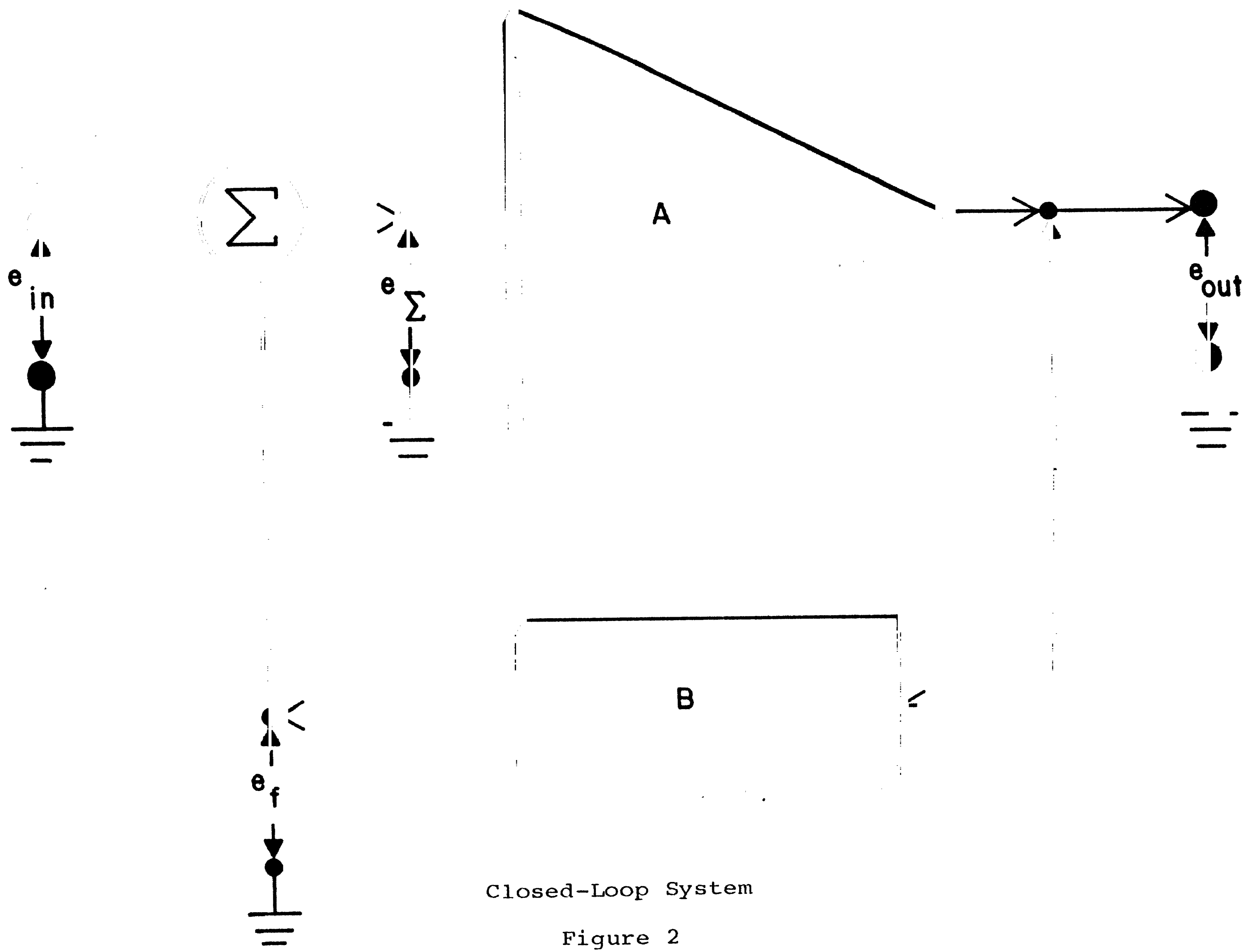


Figure 1

II. The Closed-Loop System

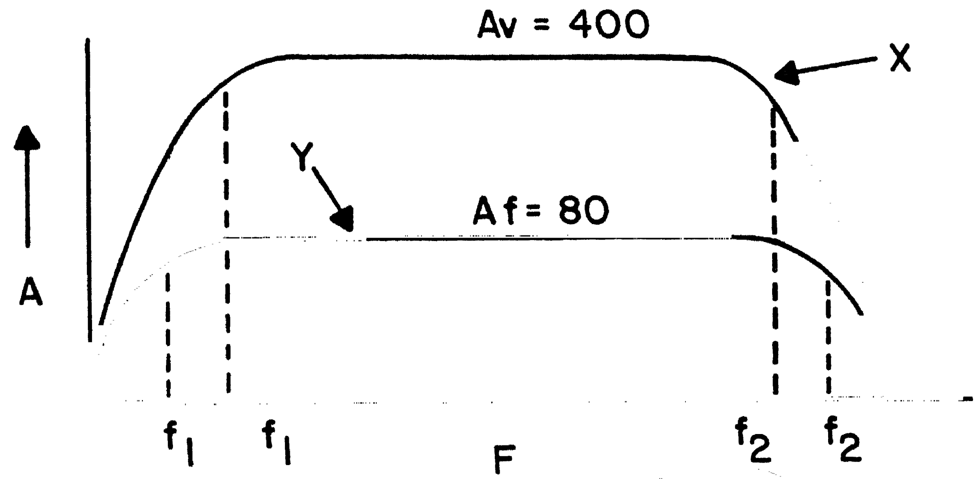


Closed-Loop System

Figure 2

III. Classes and Types of Feedback

IV. Feedback Characteristics



Frequency Response
Figure 3

V. Transistor Circuits

A. Single stage voltage feedback

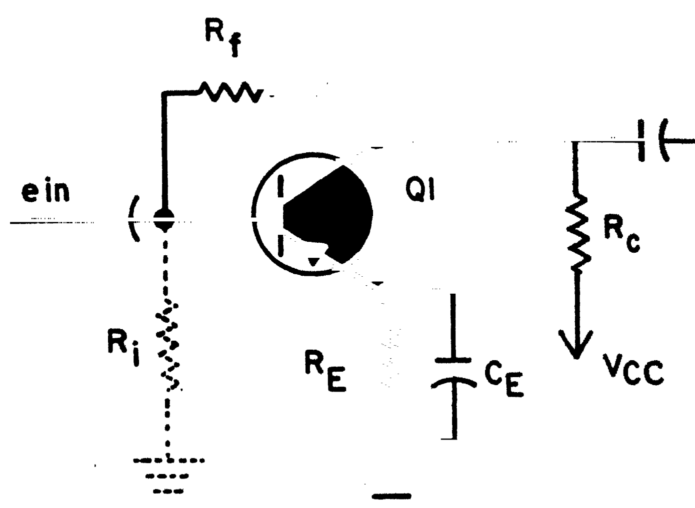
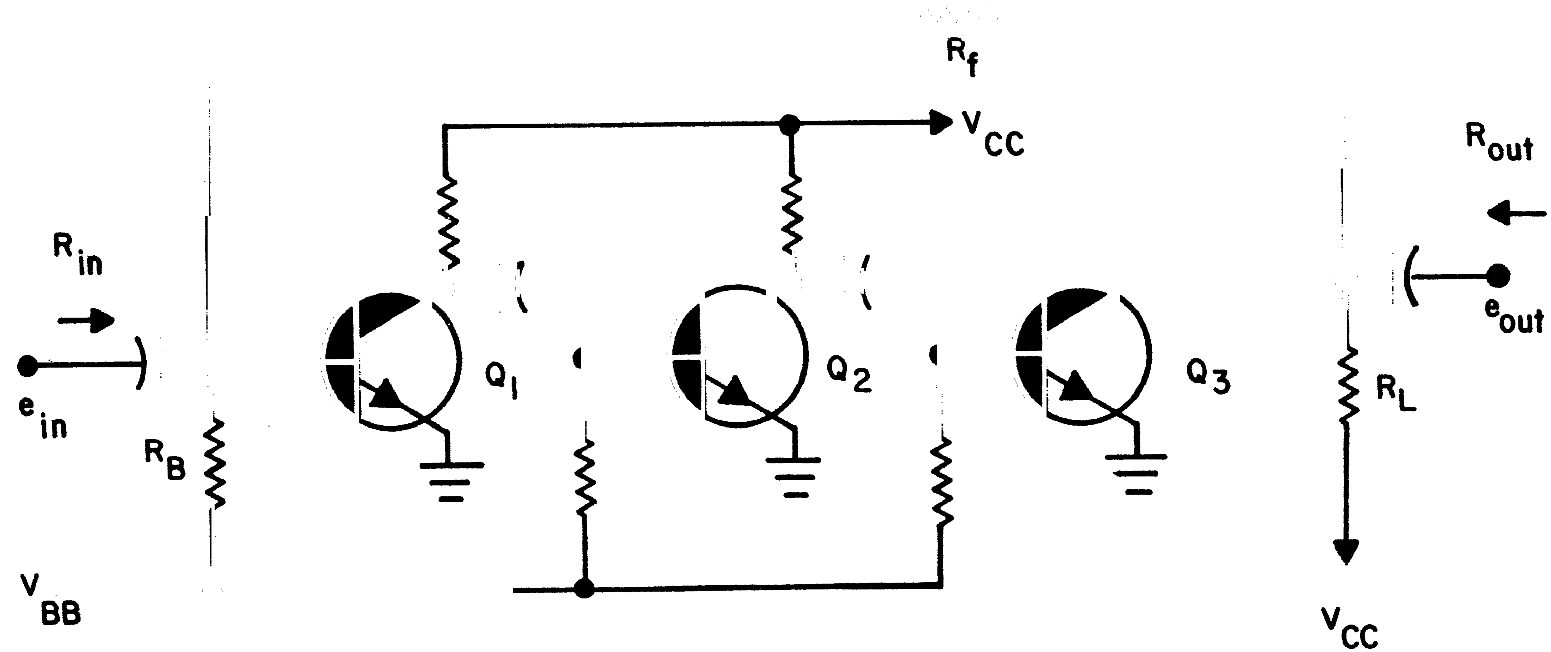


Figure 4 - Single-Stage-Voltage Feedback.

B. Multistage voltage feedback (shunt)

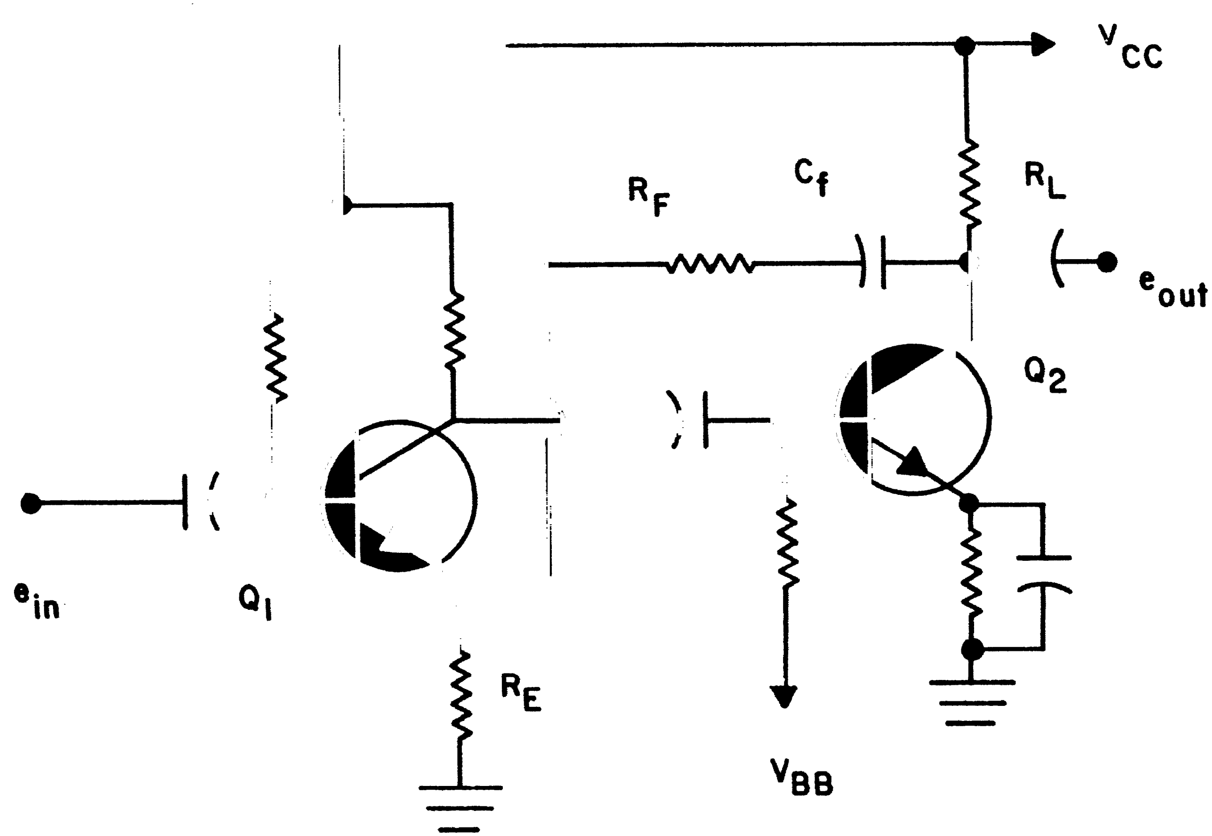
C. Multistage voltage feedback (series)



Multistage Shunt-Voltage-Feedback Amplifier

Figure 5

D. Current feedback



Multistage Series-Voltage-Feedback Amplifier

Figure 6

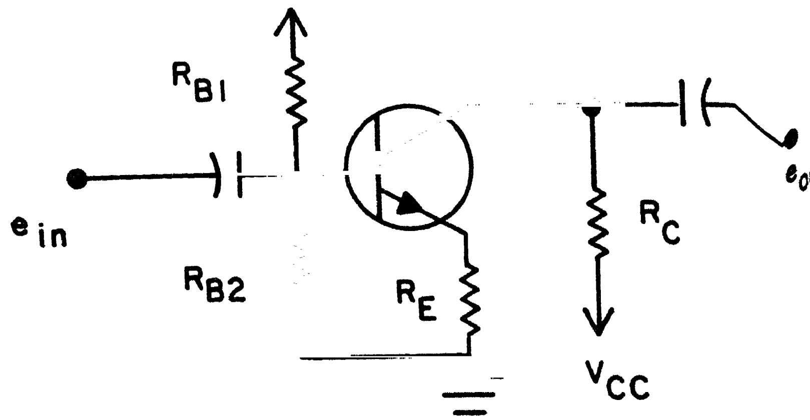


Figure 7 - Current Feedback

E. Combination feedback

INFORMATION SHEET 2.12.1I

DIRECT-COUPLED AMPLIFIERS

INTRODUCTION

Many electronic systems, ranging from voltage regulators to complex instrumentation systems, require the amplification of d-c voltages. Many times one stage of amplification is not sufficient to bring the amplitude of such signals to the required values; therefore, the different types of coupling are necessary to ensure that maximum transference of energy is required. This lesson on direct coupling and operational amplifiers is essential for the technician.

REFERENCES

1. Milton S. Kiver, Transistor and Integrated Electronics. McGraw-Hill Book Company, Fourth Edition, 1972.

2. Robert L. Shrader, Electronic Communication, McGraw-Hill Book Company, Fourth Edition, 1980.

INFORMATION

1. The following figures are labeled by title and will assist you in following the instructor through the lesson.

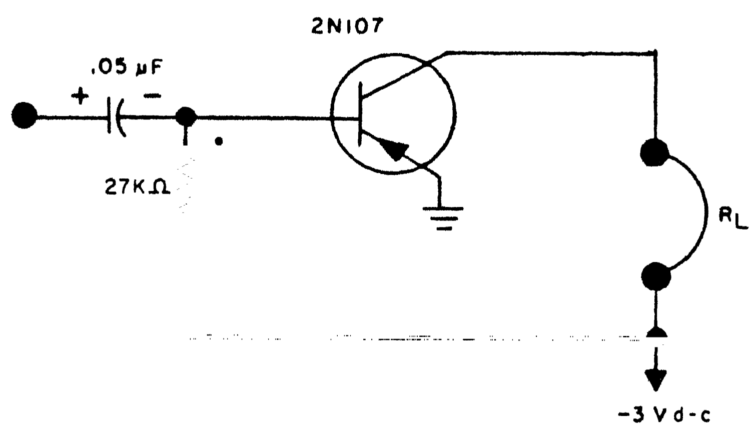
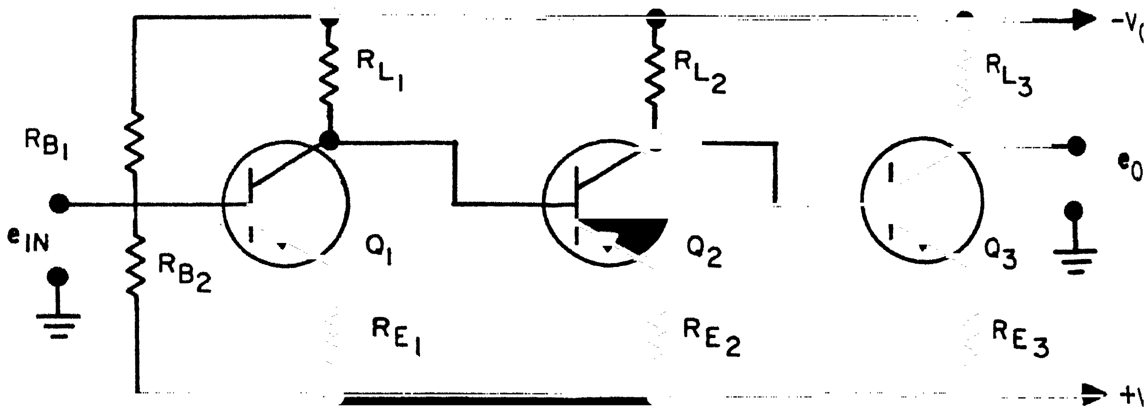
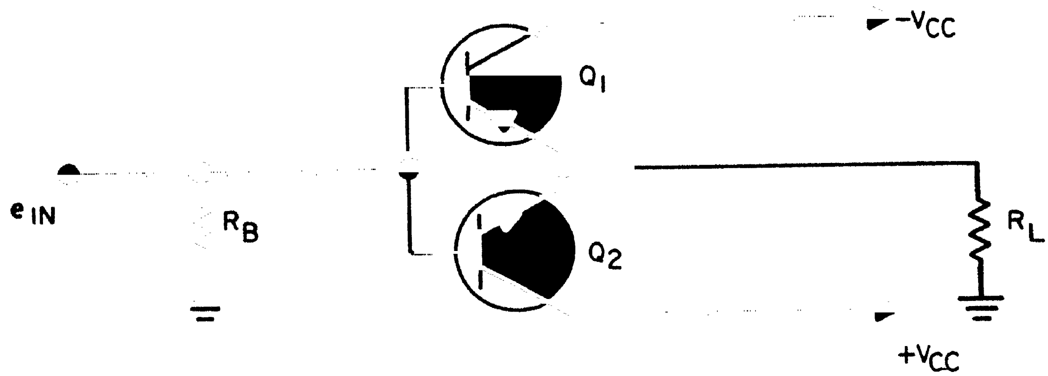


Figure 1



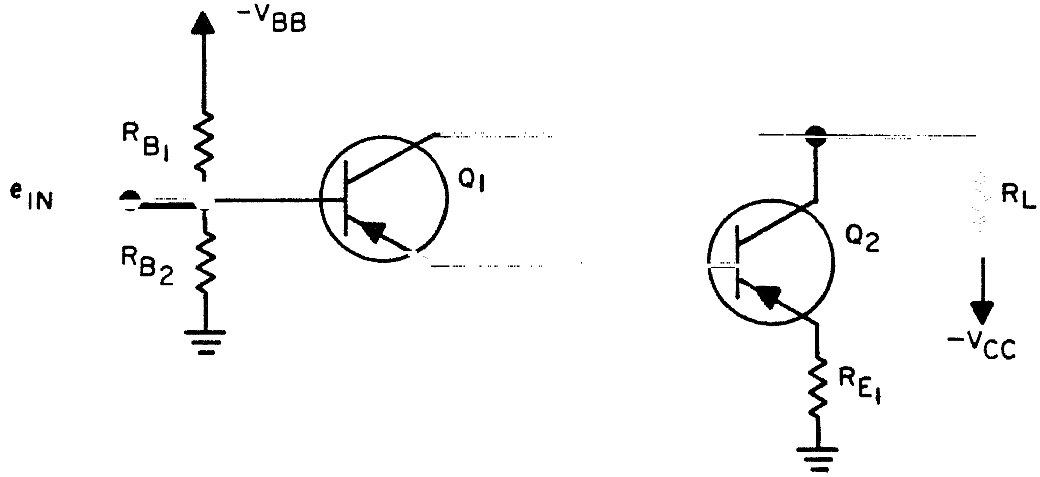
Cascaded CE d-c Amplifier.

Figure 2



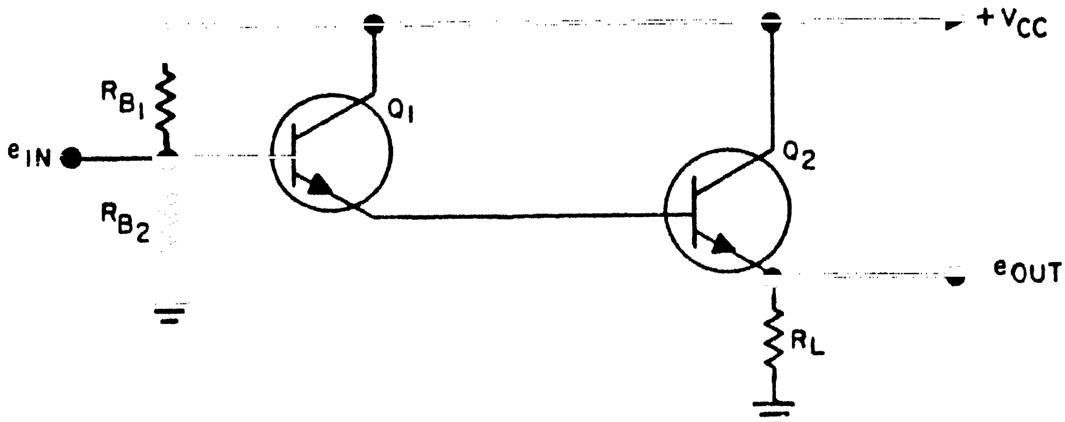
Complementary Symmetry

Figure 3



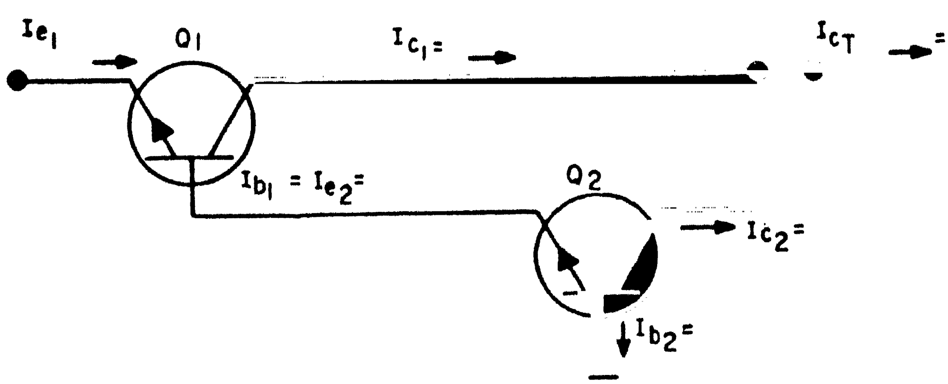
Compound-Connected

Figure 4



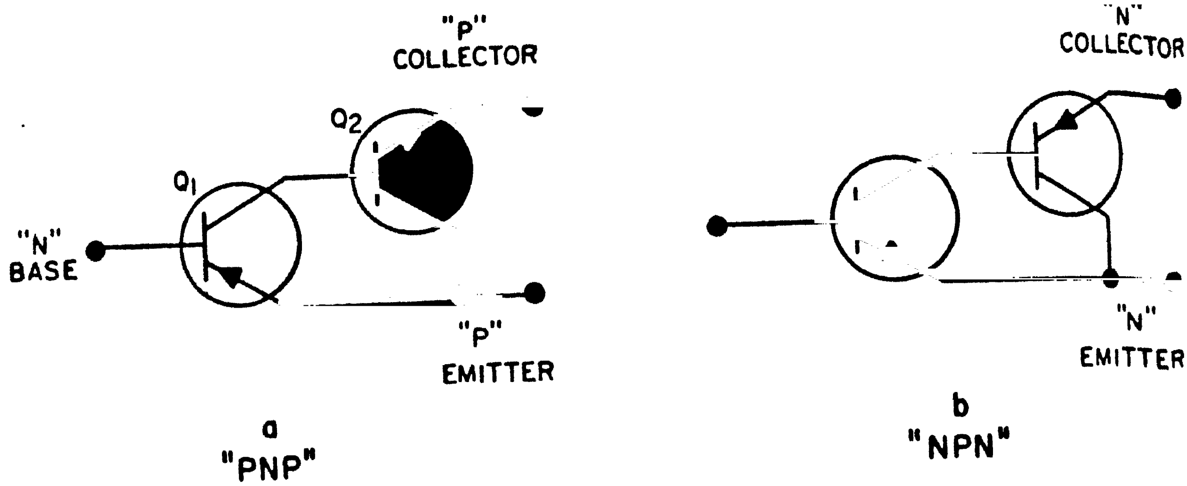
Darlington Circuit.

Figure 5



Compound Connection, CB

Figure 6



Complementary Darlington's

Figure 7

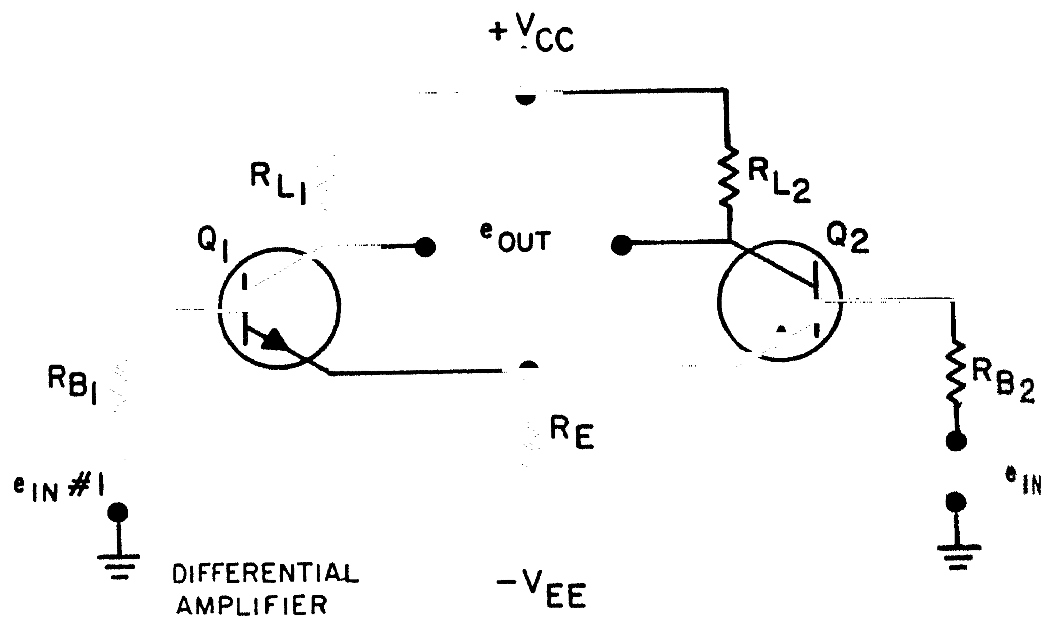


Figure 8--Modulated a-c Carrier

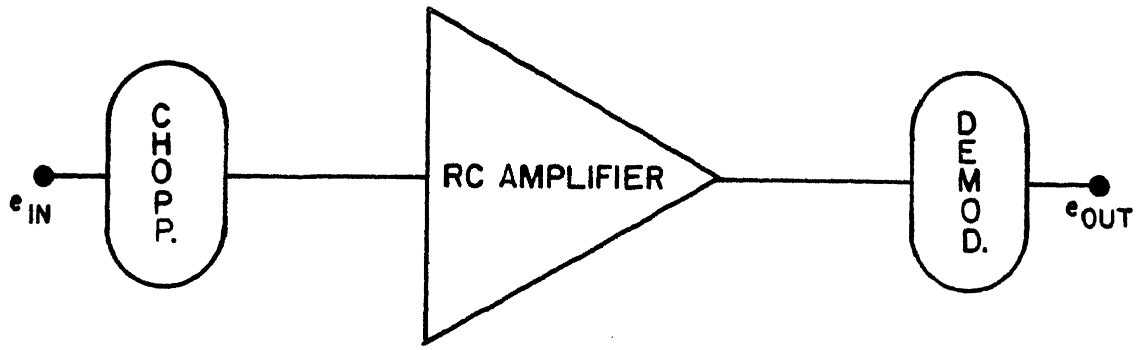


Figure 9--Chopper Amplifier

II. DIRECT-COUPLED AUDIO AMPLIFIER

A. Application

The direct-coupled audio amplifier is used where high gain at low audio frequencies or amplification of direct current (zero frequency) is desired. The direct-coupled audio amplifier is also used where it is desired to eliminate loss of frequencies through a coupling network. This circuit has numerous applications, particularly in computers, measuring or test instruments, and industrial control equipment.

B. Characteristics

1. Uses common-emitter circuit for high gain.

2. Usually requires thermal stabilization to prevent runaway.

3. Frequency response extends to zero frequency (direct current).

4. Responds equally well to pulses or sine waveforms.

C. Circuit Analysis

1. General. The transistor is a device which uses the change of current flow through a resistor to produce amplifying action. D-c bias potentials are applied to the transistor elements to fix the point of operation. In a-c coupled amplifiers, the d-c biasing potentials are effectively isolated and remain unaffected by the

5. By the same type of reasoning, it can also be seen that even in the absence of an input signal a change in the gain of one stage (or the overall gain of cascaded stages), as a result of collector supply variations, will produce an output signal. Similarly, a change in bias level in any stage or on any element will be amplified proportionally, and a change of output will occur. Such changes in bias levels normally occur as a result of temperature variations, aging, difference in transistor characteristic due to manufacturing processes, or changes in transistor leakage current, and are referred to as drift.

6. The variation of the forward-bias characteristics of a typical germanium diode with temperature is shown in figure 10. The forward-bias variation is usually expressed as a change in bias voltage with temperature at a constant forward-bias current. It is usually small, but becomes significant because of the large amplification it receives because of the direct-coupling arrangement.

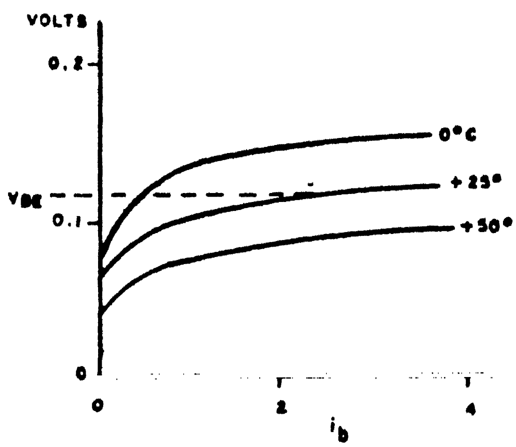
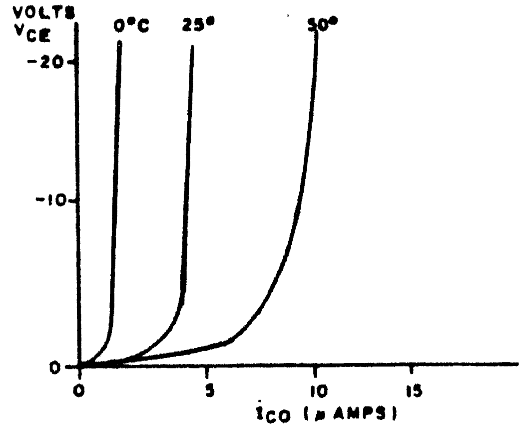


Figure 10

7. The manner in which the collector-base diode varies its reverse saturation current with temperature is also shown in figure 11 (for a typical germanium transistor). In this instance, the figure shows that the reverse-current characteristic is highly temperature-dependent, and relatively large current variations are produced as the temperature is increased.



VARIATION OF COLLECTOR-BASE DIODE REVERSE CURRENT

Figure 11

8. In a similar manner, it can be shown that the forward current transfer characteristic of a germanium transistor also varies with temperature; however, in this case the gain can either increase or decrease with temperature (silicon types generally increase with temperature). The percentage variation in gain with temperature varies greatly with the operating point, many units show a change in sign as well as magnitude The gain variation of a silicon type may be from two ten times that of a germanium type. Thus, we can see that the major sources of drift in transistors are changes in the d-c properties of the collector-base a emitter-base diodes, and changes in the d-c forward transfer ratio. Generally speaking, in comparing the operation and performance of germanium and silicon transistors, it can be said that at temperatures belc that of the reference temperature, T_O, the two types comparable. At and above the reference temperature, silicon type tends to have lower drift. The referenc temperature for silicon is 100° centigrade, and that germanium is 60° centigrade. With low source resistance, low values of drift are obtained above T_O, whi with high source resistance, the best performance oc at temperatures where the reverse-saturation collect current may be neglected.

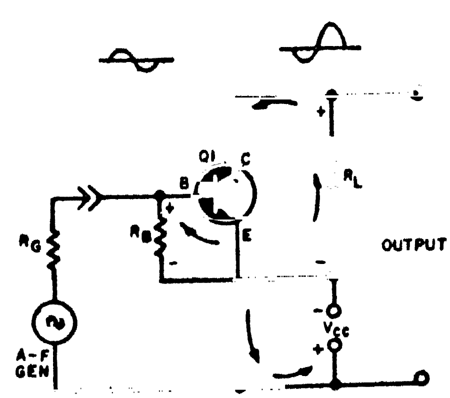
9. In d-c amplifiers, low drift is obtained by operatin with low values of collector current; this reduces t reverse-leakage current by keeping the voltage betwe the collector and the base at a low value. This vol is a forward bias for reverse current. Generally, a design precautions which reduce drift also reduce no conversely, with low noise, less drift is obtained.

When the collector current is reduced, the gain decreases and the internal emitter resistance increases. Because of the reduction of gain, the amount to which the collector current of the first stage can be reduced is somewhat limited. In single-ended amplifier stages, both the current drift and the voltage drift in the second stage tend to help cancel the input-stage drift; in a differential d-c amplifier, however, the drift in the second stage may either aid or oppose that of stage 1, depending upon the design.

10. Despite the apparent disadvantages of the d-c amplifier, it does produce (for a two-or three-stage unit) high gain and good fidelity, particularly in the low-frequency portion of the spectrum. It also provides amplification with as few parts as possible; thus, it is economical to build. In actual practice, the d-c amplifier is usually limited to one or two stages of amplification because of drift, especially where d-c must be amplified or where frequencies of 10 to 12 Hz are of importance. To overcome the effects of drift in d-c amplifiers, a special "chopper amplifier" has been developed; this amplifier converts the d-c into a-c so that the stages can be isolated and thus prevent the cumulative drift which normally occurs. This is a special type of amplifier, which will be discussed later in this section of the Information Sheet.

D. Circuit Operation

1. Basic Circuit. The schematic of a basic common-emitter d-c amplifier is shown in figure 12. the input signal is represented by the AF generator with an internal resistance equal to R_{INT}. The input signal is applied between base and emitter. Transistor Q_1 is biased by



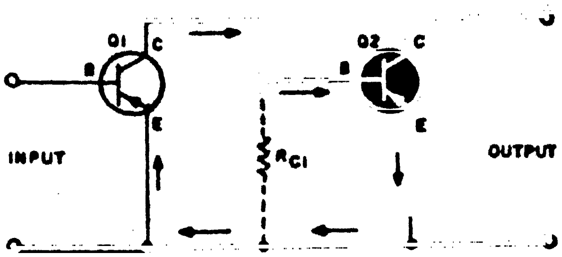
BASIC D-C AMPLIFIER (CE)

Figure 12

R_B, using the form of external PNP self-bias. (R_B and the internal resistance of the base-emitter junction form a voltage divider across the collector supply, and a forward bias is developed across R_B.) The input signa opposes the bias between base and emitter, which is normally chosen for class A operation. The direction o electron current flow through the collector output load resistor, R_L, is indicated by the arrows. The polarity of the resulting d-c voltage across the load resistor is as shown. When the positive alternation of the inpu signal is applied to the base, the base-to-emitter bias is reduced (since the signal and bias voltages are of opposite polarity). Because the base-to-emitter poten- tial is now less than the normal value, the hole curre from the emitter to the collector is lowered and electron flow through the output load resistor is reduced. The decrease in voltage drop across R_L pro- duces a negative swing and, consequently, produces a negative output signal across R_L. As the sine-wave input signal goes negative, the bias potential is aide by the input signals, and as the base-to-emitter bias is increased, more hole current flows to the collector This produces more electron flow through the collector circuit, increasing the voltage drop across R_L, and produces a positive output-signal swing during the tir that the input signal is negative. This effectively produces an opposite-polarity output signal (sometimes referred to as a 180° phase reversal). Since R_L is th load for both d-c and a-c, there is only one load line, and any internal noise voltages flowing through the load resistor add to the developed output voltage Since the output across R_L is applied directly to the base of the next stage, it can be seen that these noi components appear across the following input circuit. In an a-c coupled circuit, these noise components, co sisting of d-c or very low frequencies, are usually eliminated (blocked by the coupling capacitor). Thes noise components are produced by thermal effects, and also result from electron flow through the load resistor. They include the so-called white noise generated by diffusion-recombination effects within t transistor (similar to shot noise in the electron tub and surface and leakage noise from the transistor, wh is sometimes referred to as semiconductor or 1/f nois to distinguish it from white noise. Such noise is mostly confined to the region of from 1 to 10 Hz for white noise (in the audio range), with the semiconduc noise predominating and increasing for frequencies lo than 1 kHz. The d-c noise results from supply voltag variations. Thus, the noise components, usually elin nated by the a-c coupling capacitor in other types or amplifiers, create a design problem in the small-sign type of d-c amplifier. In large-signal amplifiers, these noises are usually masked by the large input

signal. Note also that any d-c bias changes caused by thermal instability of the stage also appear across the load, and are applied to the input of the next stage. This is an inherent disadvantage of the d-c amplifier. On the other hand, with proper input and output matching, maximum gain is obtained in the stage; moreover, with no coupling network to create a loss between stages, maximum output and efficiency are produced. Since all frequencies are present, including d-c (zero frequency) and are applied equally to the next stage, it can be understood why the d-c amplifier presents maximum gain with excellent frequency response, particularly at the lower frequencies.

2. Cascaded Stages. Because of the high gain possible per stage, many applications require only a single stage of d-c coupled amplification. Where more than one stage is required, transistors offer circuit arrangements that are not possible with electron tubes. For example, through the use of complementary symmetry, it is possible to connect the collector of the input stage directly to the input of the second stage without disturbing bias arrangements, and to use the same supply. By using alternate arrangements of NPN and PNP transistors, only one supply is needed. Recall that in the vacuum-tube d-c amplifier, as each stage progresses, the plate voltage is increased, with the grid being tapped back onto the preceding-stage plate voltage to obtain the bias. Only tandem arrangements of similar-type transistors can follow this principle. The term complementary symmetry is derived from the fact that the NPN transistor is the complement of the PNP transistor, with both circuits operating identically, but with opposite polarities. Figure 13 shows a simple direct-coupling circuit using complementary symmetry.

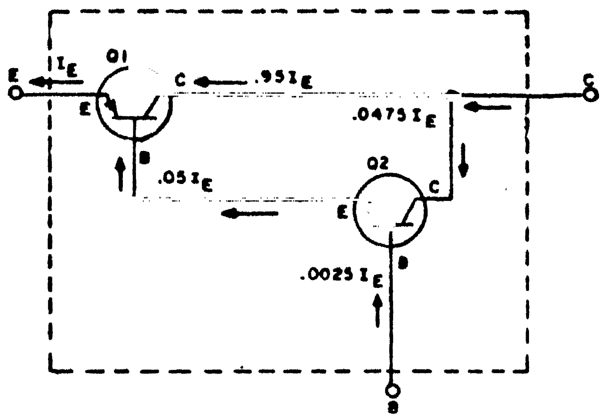


TANDEM COUPLING ARRANGEMENT

Figure 13

3. In this figure, the direction of electron flow is shown by the arrows. It is evident that the base-emitter junction of the second stage carries the collector current of the first stage. If the collector current of the first stage exceeds the maximum base-emitter current rating of the second stage, the collector resistor shown in dotted lines must be used. Otherwise, this resistor is not needed and proper design produces a saving in components. To do this, of course, the transistors must be of opposite types (NPN to PNP to NPN).

4. By the use of a special compounding connection, two transistors may be employed as a special type of d-c amplifier to obtain linearity and almost unity gain (alpha). Figure 14 shows the compound transistor connection, using the common-base configuration.



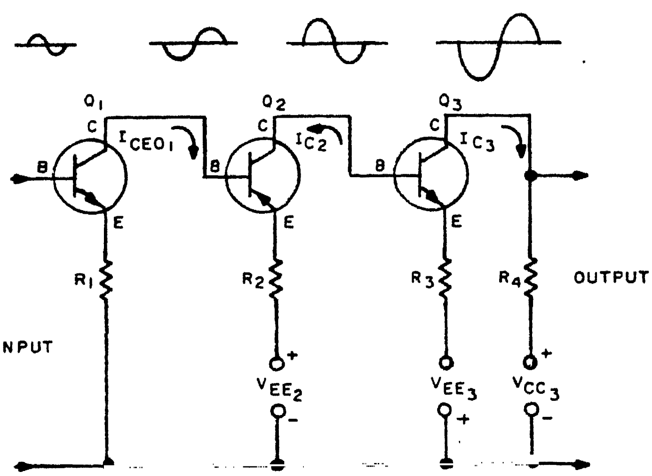
COMPOUND CONNECTION

Figure 14

Note that the input to the second stage is the base current of the first stage. Effectively, the input impedance is the series combination of the two transistors, while the outputs are in parallel. Such a circuit is roughly analogous to the push-pull electron tube circuit. Actually, this circuit is employed as a single-transistor compounded-type circuit, with emitter, base, and collector resistors used externally. The direction and relative values of current flow are shown in the figure, assuming the use of two transistors with an equal a_{fb} of .95. When these values are converted to a_{fe}, the total combination value (.9975) is equal to a gain of 399 as compared with a_{fe} of 19 for a single transistor, or more than the normal gain of two stages in cascade (19 x 19 - 381). Compounded transistors may be employed single-ended, or in complementary symmetry as push-pull stages, exactly as for single transistors.

They represent a special and unique circuit alone; however, they are shown here to illustrate how they are derived from the basic d-c amplifier. In most applications, the compounded circuits form the output stages of an amplifier, or are used as the d-c amplifier in a voltage-regulator circuit.

5. A typical three-stage, single-ended d-c amplifier is shown in figure 15. It represents the minimum of parts and d-c supplies needed for a high-gain, three-stage complementary-symmetry type of d-c amplifier for small signal applications.



TYPICAL THREE-STAG AMPLIFIER

Figure 15

As shown, the base of the input stage is completed through the input device, it is effectively open, it has no driving voltage, and zero base current exists. The collector current, I_{CEO_1}, flows through the base of stage 2, which is biased by supply V_{EE_2} in series with the emitter of stage 2. Since stage 1 uses a NPN transistor, the positive emitter bias of stage 2 is of the proper polarity to act as collector voltage for Q1. Any change in the collector current of stage 1 appears at the collector of stage 2 in amplified form; that is, $I_{C_2} = B_2 I_{CEO1}$, where B_2 is the current gain of stage 2. Stage 2 uses a PNP transistor; therefore, by complementary symmetry, stage 3 must also be an NPN stage similar to stage 1. The emitter bias for stage 3 is supplied through V_{EE_3}, which is connected positive to ground. Thus, the collector supply of stage 3 (V_{CC_3}) is of series-aiding polarity, and the total collector voltage is that of both the collector and emitter supplies of stage 3. In a similar manner, the collector voltage

of stage 2 is supplied by B_{EE_2} and V_{EE_3}. The collector current of stage 2 is the base current of stage 3. The output of the amplifier appears across collector resistor R4, and the collector current is that of stage 2 multiplied by the amplification factor, or $I_{C3} = B_2B_3I_{CEO}$. Emitter resisistor Rl, R2, and R3, which are of a low value, provide degenerative feedback; they also act as emitter-swamping resistors to help stabilize the amplifier with respect to temperature variations.

Assuming that the input stage has a collector current of 5 µA and assuming a gain of 38, the second stage will have a collector current of 190 µA. With a gain of 40, the third stage collector current will be 7.6 mA. It is clear that any slight change in the current of stage 1 caused by temperature or noise will be greatly amplified and appear at the output of stage 3. With such sensitivity and amplification, therefore, it is almost mandatory that such an amplifier be temperature-compensated, even if room temperatures do not vary excessively. Naturally, the amplitude of the input signal must be limited if true fidelity is to be obtained. Driving the transistor into cutoff and saturation would clip the peaks of the signal, just as an electron-tube operation. It is also evident that low-noise transitors must be used; otherwise, the noise might mask the signal. Note that in this amplifier the small emitter bias of stage 2operates as the collector voltage of stage 1. Low collector voltage is used to minimize noise generated in the input stage.

INFORMATION SHEET 2.12.2I

OPERATIONAL AMPLIFIER FUNDAMENTALS

INTRODUCTION

1. The operational amplifier is an extremely efficient and versatile device. Its applications span the broad electronic industry filling requirements for analog instrumentation, analog computation, and special system design.

2. Originally, the term "Operational Amplifier" was used in computing to describe amplifiers that performed various mathematical operations. It was found that the amplification of negative feedback around a high gain d-c ampifier would produce a circuit with precise gain characteristics that depended only on the type and amount of feedback used. By the proper selection of feedback components, operational amplifier circuits could be used to add, subtract, multiply, divide, integrate and differentiate.

3. As practical amplifier techniques became more widely known, it was apparent that these feedback techniques could be used in many control and instrumentation applications. Today, the general use of operational amplifiers has been extended to include such applications as d-c amplifiers, a-c amplifiers, comparators, servoamplifier, deflection yoke drivers, and a host of others.

4. What the operational amplifier can do is limited only by the imagination and ingenuity of the user. With a good working knowledge of its characteristics, you will be able to exploit more fully the useful properties of operational amplifiers.

REFERENCE

Transistor and Integrated Electronics, Kiver, McGraw-Hill, Fourth Edition, 1972, pages 271-305

INFORMATION

A. Definition - An operational amplifier is a high gain, direct-coupled (d-c) amplifier utilizing degenerative feedback for control of its amplification factor.

B. Purpose

1. Operational amplifiers perform no computation by multiplication; i.e., the input voltage is multiplied by amplifier gain. $E_o = E_{in} A$. If the gain (A) is less than one, then the operational amplifier is dividing. For example, an amplifier with a gain of .5 will always multiply its input by 1/2.

2. Gain itself is determined by the ratio of input voltage to output voltage.

   $A = \frac{E_o}{E_{in}}$. The voltage gain of an operational amplifier is a ratio of $E_o : E_{in}$.

3. However, the amplifiers do improve the performance of various computing loops, by accomplishing the following: reversing the sign of a voltage with or without a change i scale factor; isolate or eliminate the loading of one computing element from another; provide a voltage proportiona to the algebraic sum of two or more input voltages. Due t the various functions performed by operational amplifiers, they are called by several names; computing amplifier, isolation amplifier, feedback amplifier, and summation amplifier.

C. Functional analysis

1. Amplifier section

   a. In order to better understand operational amplifiers, we will first go through the different portions of th operational amplifier.

   b. The heart of the operational amplifier is the amplifi section. It is represented by the triangle in figure 1. It contains an odd number of direct-coupled (d-c) amplifiers, usually three or five stages. The odd number of amplifiers are required to provide 180 degrees of phase shift from input to output. The outpu voltage will always be oppostie or inverted with respect to the input polarity to provide degenerative feedback.

   c. Open loop gain, that is the gain of the amplifiers without feedback, is from 1 x 10^3 to 2 x 10^6 but it i usually around 50 x 10^3 or 50 k; 92 dB.

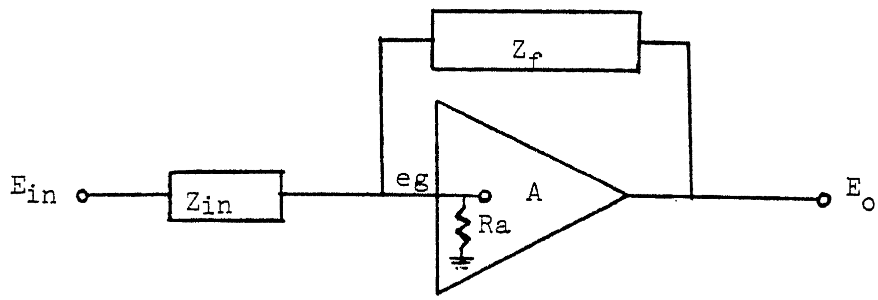


Figure 1

d. In figure 2, is an expanded view of the amplifier section in block diagram form.

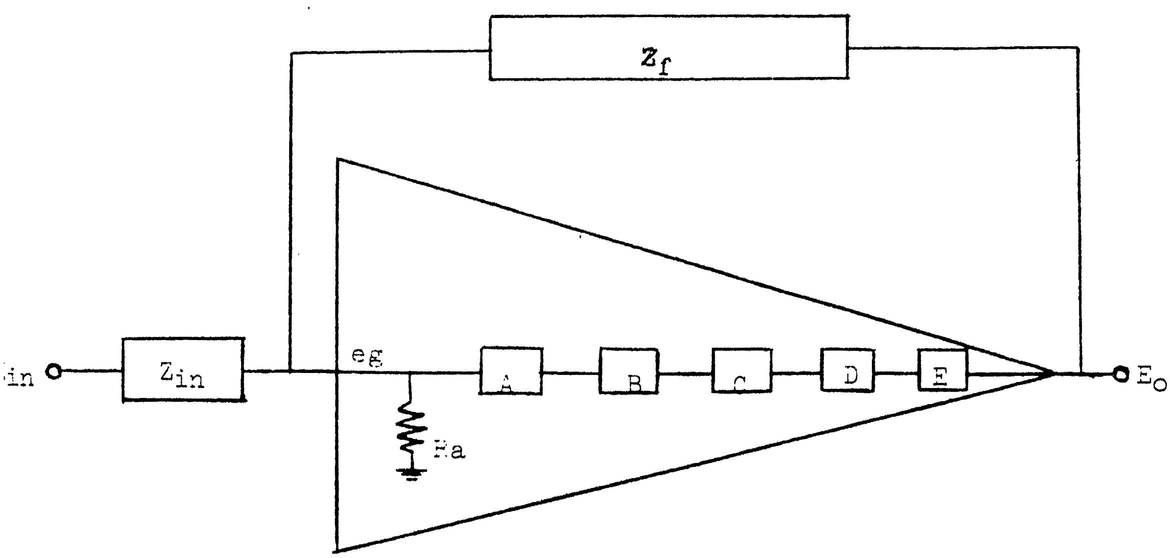


Figure 2

e. Block A is the input stage. It usually consists of a cathode follower (in tube types) or an emitter follow in transistors. This gives isolation for the amplif section. If, however, an external stabilization circuit is used, then the input stage is a different amplifier.

f. Blocks B through D are the d-c amplifiers. With a stage gain of only 100 then the over gain of the circuit would be 1,000,000 1 x 100 = 100 x 100 = 10k 100 = 1,000,000. Because there is an odd number of stages, phase inversion always occurs.

g. The final stage again will be either a cathode follo or an emitter follower for further isolation.

h. R_a is the base or grid resistor for the first stage. It develops e_g or the input potential for the amplif section.

i. The effective input impedance is very low. It may b found by the formula Z_{in} (of amplifier section) $= \frac{Z_f}{1+}$ Some typical values are:

Z_f = 1 megohm

A = 50k

If they are put into the formula, then $\frac{1M}{1+50k} = 20\ \Omega$ approximately. The effective input impedance is ver low.

j. The amplifier section's output impedance is also low Z_o of the amplifier section may be found by using th formula

$$Z_o = \frac{r_p}{1+AB} \text{ where}$$

r_p = plate resistance of the final amplifier sta

B = ratio of input impedance to the sum of input and feedback impedance

$$B = \frac{Z_{in}}{Z_f+Z_{in}}$$

with some typical values $r_p = 50k\Omega$

B = .5 if both Z_f and Z_{in} are 1M, A = 50k, then is approximately 5 ohms. Some typical values of Z_o are 5 to 10 ohms.

k. Since Z_o is small, the output voltage is essentially independent of load current.

2. Computing impedances

   a. Z_f and Zi_n are the computing impedances. They may be either resistors or capacitors; i.e., resistance or capacitive reactance. According to the ratio of impedances, and the type of impedance, specific functions such as algebraic summation, multiplication or division by a constant, differentiation, integration and other special function circuits.

   b. The input impedance, Z_{in}, is usually in the 500 k to 10 megohm range. It couples the input voltage from the preceding stage. It is also used as a current summing network to reduce E_{in} to e_g the input voltage to the amplifier section.

   c. The feedback impedance Z_f is also in the 500 k to 10 megohm range. It develops the output voltage E_o and couples the feedback current and voltage form output to input.

Theory of operation

1. The function of the circuit in figure 3 is to reverse the sign of the voltage, and give a gain of -1.

2. Operation

   a. The input voltage E_{in} causes a current I_{in} to flow through Z_{in}.

$$I_{in} = \frac{E_{in}}{Z_{in}}$$

   b. If E_{in} is a positive voltage, then R_a will develop a small positive voltage (e_g) at the input to the amplifier section. The amplifier section will amplify e_g and invert it (odd number of stages) causing a negative E_o.

   c. The resulting difference of potential between the input terminal and output terminal will cause a current (I_{fb}) to flow through Z_f.

$$I_{fb} = \frac{-E_o}{Z_f}$$

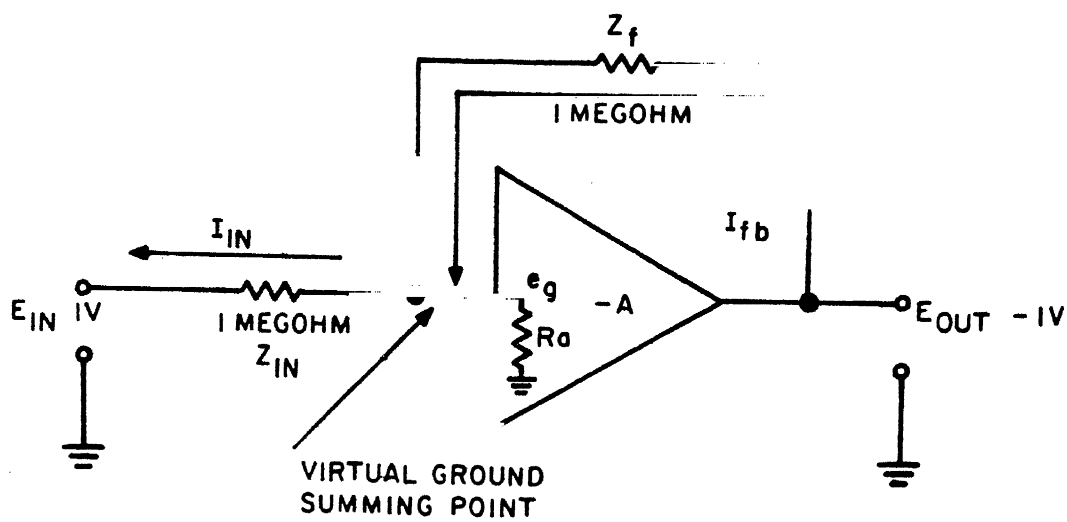


Figure 3

BASIC OPERATIONAL AMPLIFIER OPERATION

$$\text{Gain} = \frac{Z_f}{Z_{in}}$$

$$E_o = \frac{Z_f}{Z_{in}} E_{in}$$

d. Since an amplifier operating class A has very little grid or base current, the I_{in} appears in series with I_{fb}. The voltage potential e_g is almost zero during operation. The current through R_a is on the order of 1×10^{-4} µA and may be disregarded.

e. In figure 4, the external current flow is shown.

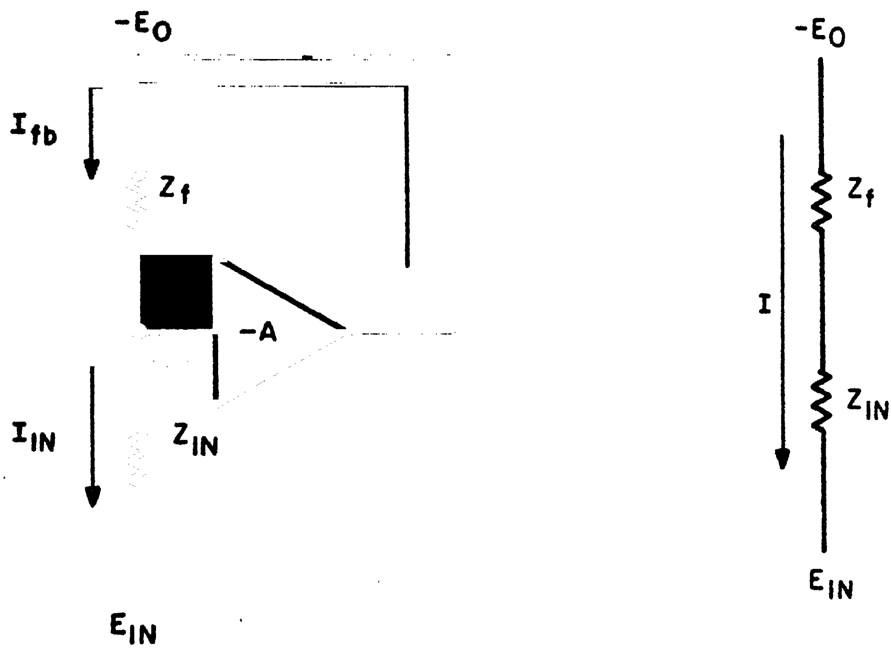


Figure 4

I_{in} and I_{fb} appear in series and in series circuits all currents are equal.

f. Since $I_{in} = I_{fb}$, then by algebraic substitution:

$$I_{in} = \frac{E_{in}}{Z_{in}} \ ; \quad I_{fb} = \frac{-E_o}{Z_f}$$

$$\frac{E_{in}}{Z_{in}} = \frac{-E_o}{Z_f}$$

g. Solving for E_o; multiply by $(-Z_f)$.

$$(-Z_f)\left(\frac{E_{in}}{Z_{in}}\right) = \frac{+E_o}{Z_f}(+Z_f)$$

$$E_o = \frac{-Z_f}{Z_{in}} E_{in}$$

h. The formula $E_o = \frac{-Z_f}{Z_{in}} E_{in}$ is the basic formula for the output voltage of any operational amplifier.

i. Remember that the gain of any amplifier is a ratio of $\frac{E_o}{E_{in}}$. In an operational amplifier then $\frac{E_o}{E_{in}} = \frac{Z_f}{Z_{in}}$ by transposing the formula. The gain of the operational amplifier is determined by the ratio of $\frac{Z_f}{Z_{in}}$. Whatever its circuit configuration and its function in the circuit.

j. In figure 3, then, with an input voltage of 1V and Z_{in} = 1M; Z_f = 1M. $E_o = \frac{-1M}{1M}$ 1V = -1V = Eo. Sign inversion and a gain of negative one.

k. The feedback current (I_{fb}) is determined primarily by Z_{in} and E_{in} and I_{fb} will equal I_{in} at all times.

l. With 1V in and Z_f and Z_{in} both 1 megohm then:

$$I_{in} = \frac{E_{in}}{Z_{in}}$$

$$I_{in} = \frac{1V}{1M}$$

$$I_{in} = 1\mu A$$

I_{fb} is equal to $\frac{Z_o}{Z_f}$

$$I_{fb} = \frac{-1V}{1M}$$

$$I_{fb} = 1\mu A$$

$$I_{fb} = I_{in}$$

m. If Z_{fb} is increased to 2 megohms with both Z_{in} and E_{in} remaining unchanged, then E_o = -2V.

$$I_{fb} = \frac{E_o}{Z_f}$$

$$= \frac{-2V}{2M}$$

$$b = 1\mu A$$

Note that I_{fb} did not change even though Z_f changed. This determines E_o.

n. Multiplication is performed when the $\frac{Z_f}{Z_{in}}$ ratio is greater than 1.

$$\frac{Z_f}{Z_{in}} > 1 \text{ - multiplication}$$

o. Division may be performed if the $Z_f{:}Z_{in}$ ratio is less than one.

$$\frac{Z_f}{Z_{in}} < 1 = \text{division}$$

p. The voltage eg is very small and may be determined from the formula

$$E_o = E_{in} A$$

The voltage eg is equal to $\frac{E_o}{A}$ where A is the open loop gain of the amplifier section.

$$eg = \frac{E_o}{A}$$

with a + 1V as E_{in} and Z_f of 2M and Z_{in} of 1M, then E_o = -2V.

$$eg = \frac{-2V}{50k} \text{ - open loop gain.}$$

$$eg = 40\ \mu V$$

q. The voltage at this point is called virtual ground. The effective impedance is very small. Current flows toward this point and away from it acting as a ground.

r. The operational amplifier constantly seeks to obtain this virtual ground. So, when E_{in} increases or decreases, E_o must correspondingly change, by amplifier action, to cause a current to flow through Z_f that just balances the current flow through Z_{in}.

s. Operational amplifiers are self regulating. If E_o increases due to amplifier gain, component variation, etc.

(1) Feedback increases.

(2) Eg would decrease.

(3) Overall circuit gain decreases.

(4) E_o returns to its correct value.

If E_o decreases due to amplifier changes;

(1) Feedback voltage decreases.

(2) Eg increases.

(3) Overall circuit increases.

(4) E_o returns to its correct value.

t. The operation of the amplifier with its Z_f and Z_{in} is to keep virtual ground at near zero potential, then and I_{fb} will appear in series. Circuit gain will be determined by ratio of Z_f/Z_{in}.

u. The input impedance of an operational amplifier is high; its output is low. Input impedance is Z_{in}. Th makes an operational amplifier a very good isolation device.

F. Chopper Amplifiers

1. One problem which adversely affects the usability of operational amplifier for accurate computations is drift the d-c amplifier. Drift refers to a variation in output voltages that is independent of the input signal. Any s variation, of course, would result in a computational error.

2. Amplifier drift is primarily attributed to variations in supply voltages, circuit components, and filament voltage for tube-type amplifiers, and in temperature for the transistorized versions.

3. Much of the solution to the drift problem exists in standard design techniques such as the use of well-regulated power supplies, special cooling arrangements for controlling ambient temperature, temperature-compensating devices in transistor circuits, and carbon film and wire-wound resistors operating at a fraction of their rated power dissipation.

4. The chopper amplifier is used for automatic balancing or drift control. This technique employs a modulator to convert the d-c low-frequency to a higher-frequency signal which can then be amplified by a high-gain, drift-free a-c amplifier. To recover the original signal, the a-c signal is passed through a demodulator.

5. An electromechanical vibrator or chopper is frequently used as the modulating-demodulating device, since it is rugged and drift-free and one unit acts as both the modulator and demodulator.

6. How the chopper is used is shown in figure 5. The basic circuit is shown in (A) and associated waveforms are shown in (B). The chopper, in synchronism with the a-c supply frequency, chops (modulates) the input signal and rectifies the amplified output of the a-c amplifier. The low-pass filter at the input prevents higher-frequency components from passing through the a-c amplifier, and the filter at the demodulator and recovers the a-c and low-frequency components and attenuates the higher-frequency components, including the chopping of carrier frequency.

7. Note that the chopper amplifier is phase-sensitive; a sign change of the d-c input results in a 180° phase reversal of the a-c voltage and a corresponding sign change of the filtered d-c output. In figure 5 the output is shown out of phase with the input. By adding or deleting one stage in the a-c amplifier, the output could be made to be in phase with the input.

8. When the drift-free chopper amplifier is combined with a conventional d-c amplifier, as shown in figure 6, automatic correction for drift is accomplished. The circuit is commonly called an automatically balanced or a chopper-stabiized operational amplifier.

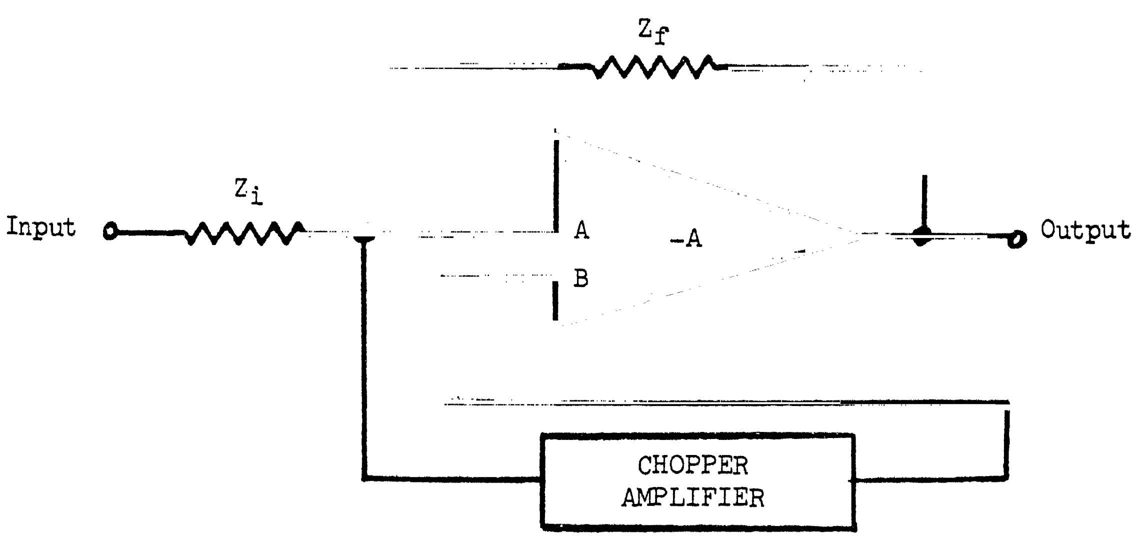
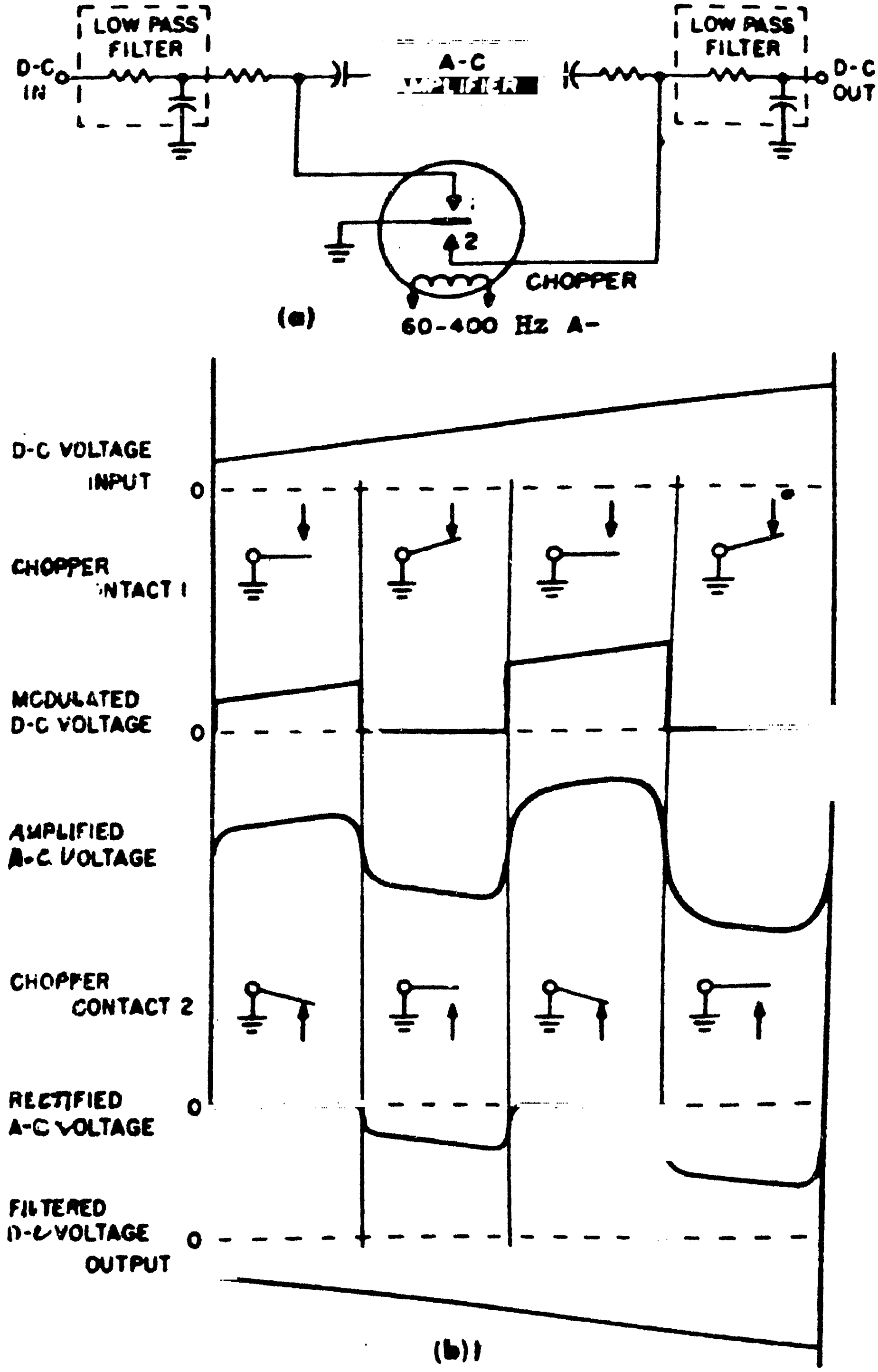


Figure 6



The chopper amplifier.

Figure 5

9. To understand the automatic balancing action, assume that a positive d-c or slowly changing drift voltage appears at the output terminals. (This would be analogous to a negative input at the A terminal of the d-c amplifier.) The error voltage would be fed back through Z_f and, after processing by the chopper amplifier, would end up as a negative balance signal at the B terminal, reducing the output offset voltage to zero. A similar action occurs for negative drift voltages except that the polarities of the involved signals would be reversed.

10. To illustrate the properties of high-quality computer amplifiers using chopper stabilization, some representative specifications are tabulated below:

    a. Gain of the d-c amplifier channel, 30,000 to 150,000.

    b. Gain of the automatic balancing channel, 2000 to 3000.

    c. Total d-c gain, 25 x 10^6.

    d. Grid current, less than $10^{-4}\mu A$.

    e. Average drift over an 8-hour period, 20 to 200μV.

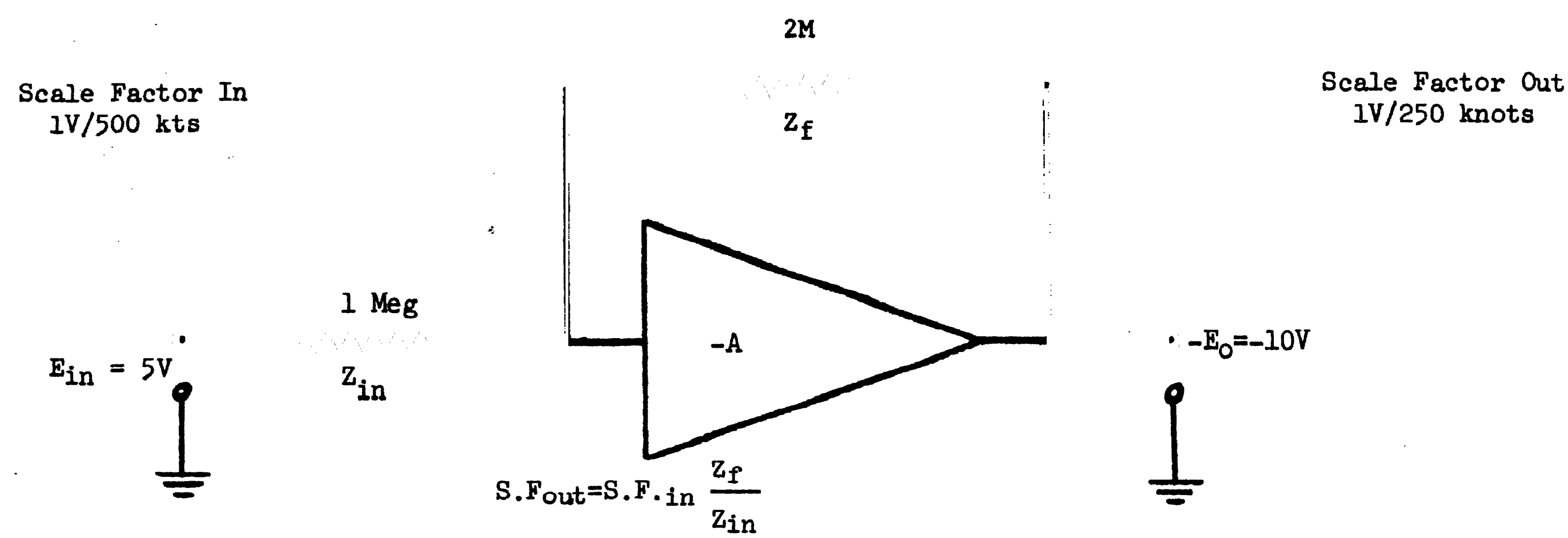
    f. Linear output range, at least ± 100 volts into rated load; decreases above 100 Hz, depending on tube types.

G. Scale Factors

1. An input scale factor will be changed by the gain of an amplifier. In an isolation amplifier with a gain of -1, Z_f/Z_{in} ratio of one, there will be no scale change. There is no change in analog units; therefore, no change in scale factor. If the gain of the circuit is more or less than one, the scale factor must be changed.

2. The identity process is used to change scale factors.

    a. If the output voltage is different from the input voltage, then the ratio of analog units to equation units must also change. Refer to figure 7. In figure 7, the Z_f to Z_{in} ratio is -2. With 5V in, E_{out} is -10V. The input voltage represents 2500 knots; therefore, by the law of identity the output voltage must also represent 2500 knots. This means the scale factor must be changed. The output voltge would represent 5000 knots, unless the scale factor is changed.



BASIC SCALE CHANGING OPERATIONAL AMPLIFIERS

Figure 7

b. To compute the change in scale factor, use the formula:

$$\text{Scale factor out} = (\text{scale factor in}) \left(\frac{Z_f}{Z_{in}}\right)$$

$$SF_o = SF_{in} \frac{Z_f}{Z_{in}}$$

$$SF_o = (1V/500 \text{ kts})\left(\frac{2}{1}\right)$$

$$SF_o = \frac{2}{500}$$

$$SF_o = \frac{1V}{250 \text{ kt}}$$

c. The new scale factor 1V/250 kts, the output voltage still represents 2500 knots.

$$\text{Equation units} = \text{S.F.} \times \text{analog units}$$

$$= (1V/250 \text{ kts})(-10V)$$

$$2500 \text{ kts out} = 2500 \text{ kts in}$$

3. In analog devices, input variables must be scaled to represent the same information (equation units) in different modules of the device. This may be accomplished by the circuits shown in figure 8. Note that the input information to amplifier #1, 250 knots of airspeed from the airspeed circuits is represented by 5V at a scale factor

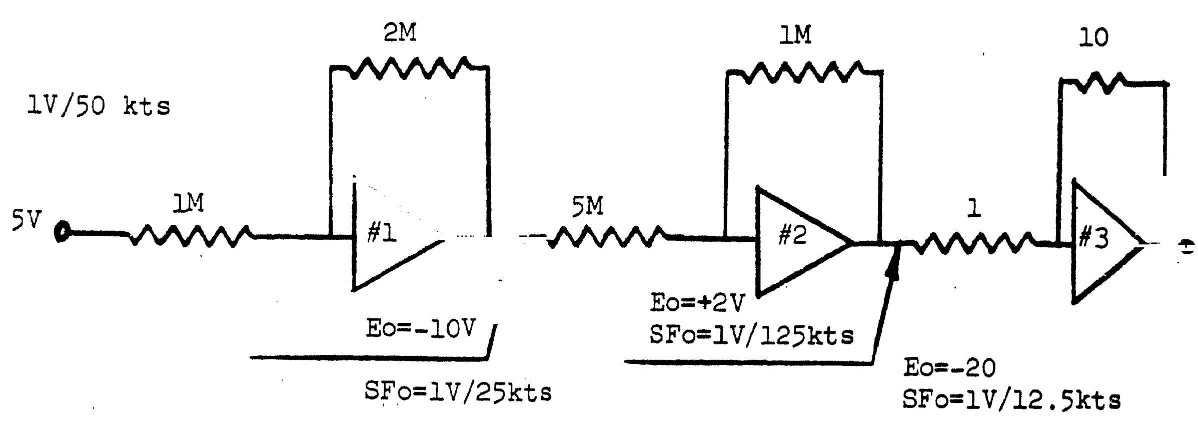


Figure 8

of 1V/50 kts. Throughout the circuit, the equation units remain the same. However, the proper application of scale factors and the law of identity allow the information to be represented by four different voltages, as shown in figure 9.

	E_{in}	Scale factor in	Represents	E_o	Scale factor out	Represents
Amp #1	5V	1V/50 kts	250 kts	-10V	1V/25 kts	250 kts
Amp #2	-10V	1V/25 kts	250 kts	+ 2V	1V/125 kts	250 kts
Amp #3	+2V	1V/125 kts	250 kts	-20V	1V/12.5 kts	250 kts

Figure 9

H. Basic Operational Amplifier Circuits

1. The circuits covered below are some basic operational amplifier circuits covered in outline form. These are only basic circuits. There are many more.

2. Summing Amplifiers are used as an electronic summation circuit. E_o represents the algebraic sum of input voltages.

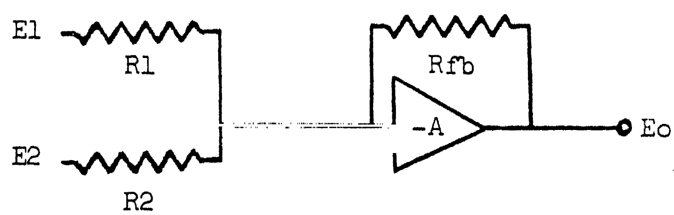


Figure 10

Summing Amplifier

Definition - An operational amplifier with more than one input.

3. Operational amplifier switch operates as a switch with its operating point determined by the bias potentiometer R3.

   a. With no voltage present on R1 and with E2 a negative voltage, the output voltage will be positive causing diode CR_1 to conduct.

   b. Resistance of CR_1 when conducting is very low.

   c. Output voltage would be near zero.

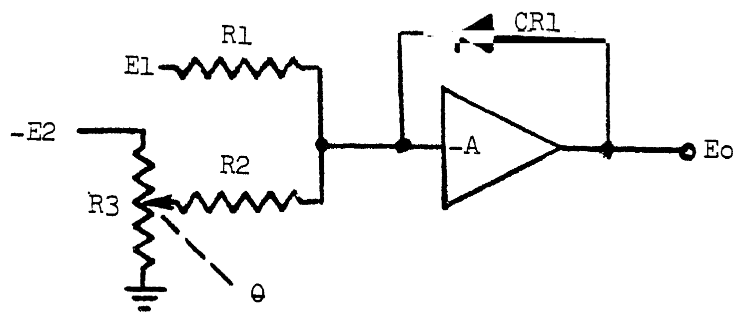


Figure 11

Operational Amplifier Switch

d. Recall that resistance of conducting diode is about 100 ohms.

(1) $E_o = \frac{-Z_f}{Z_{in}} E_{in}$

(2) $E_o = \frac{-100}{1M} E_{in}$

(3) E_o is very small

e. When input potential on R1 becomes sufficiently positive to drive input to a positive voltage E_o will become negative and diode CR_1 becomes reversed biased.

f. The feedback impedance increases and gain switches from low to high.

g. If a specific gain is desired, a resistor is placed in parallel with the diode.

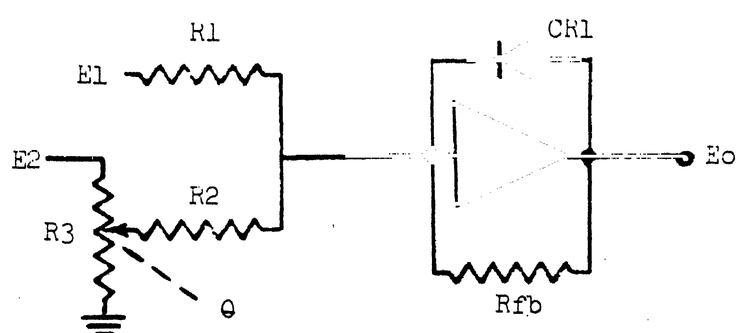


Figure 12

(1) When diode is forward biased, all feedback curren
flows through diode.

(2) When switching occurs, diode's resistance is much greater than resistor (R_{fb}) and feedback current flows through resistor (R_{fb}).

(3) The result is a specific gain at switching point for controlled inputs.

4. Logarithmic amplifier

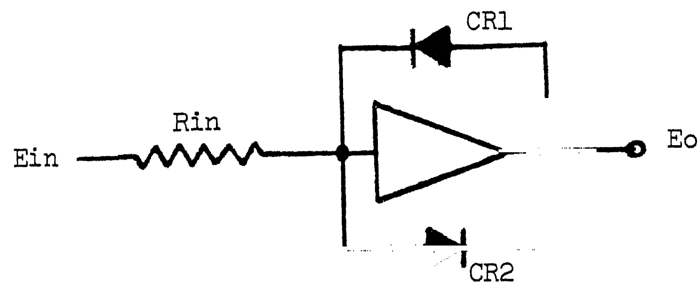


Figure 13

Logarithmic Amplifier

a. Diodes CR_1 and CR_2 are special function diodes with variable conduction level.

b. Two diodes are used so that there may be both positi and negative inputs.

c. As input voltage increases in amplitude, one diode c the other, depending on the polarity of the input, conducts.

(1) As diode conducts harder, current flow increases

(2) It seems as if Z_f had decreased.

d. This results in a logarithmic gain for this circuit.

(1) High gain for small signals because of low conduction, therefore high resistance of diode.

(2) Low gain for larger signals.

5. Integrating Operational Amplifier

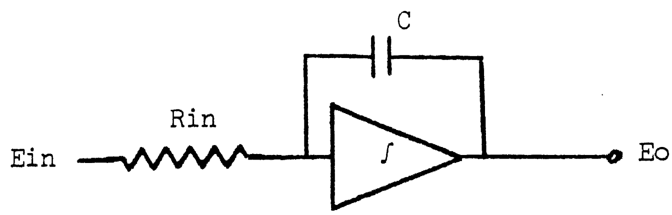


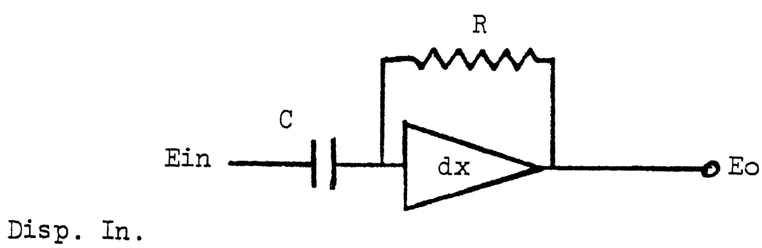
Figure 14

Integrating Amplifier

a. Integrates input voltage with respect to time by accumulating charge on capacitor.

b. For example, if an input voltage waveform represented acceleration, the output voltage would be the integral of acceleration, i.e. velocity.

6. Differentiating Amplifier



$$\frac{ds}{dt} = V \text{ out}$$

Figure 15

Differentiating Amplifier

a. Differentiates input voltage.

b. Output voltage represents derivative of input.

c. For example, if the input voltage represented displacement, then the output would represent ds/dt or V.

NOTETAKING SHEET 2.12.1N

DIRECT-COUPLED AND OPERATIONAL AMPLIFIERS

REFERENCES:

1. Electronic Circuits, NAVSEA 0967-LP-000-0120, pages 5-279 tc 5-318.

2. Transistor and Integrated Electronics, Kiver, M. S., McGraw-Hill, Fourth Edition, 1972, pages 306 to 310.

3. Integrated Circuits and Semiconductor Devices, Deboo and Burrous, McGraw Hill, Second Edition, 1977, Chapter 4.

4. Electronics Communication, Schrader, R. L., McGraw Hill, Fourth Edition, 1980, pages 216 and 317.

NOTETAKING OUTLINE:

I. Direct-Coupled Amplifiers

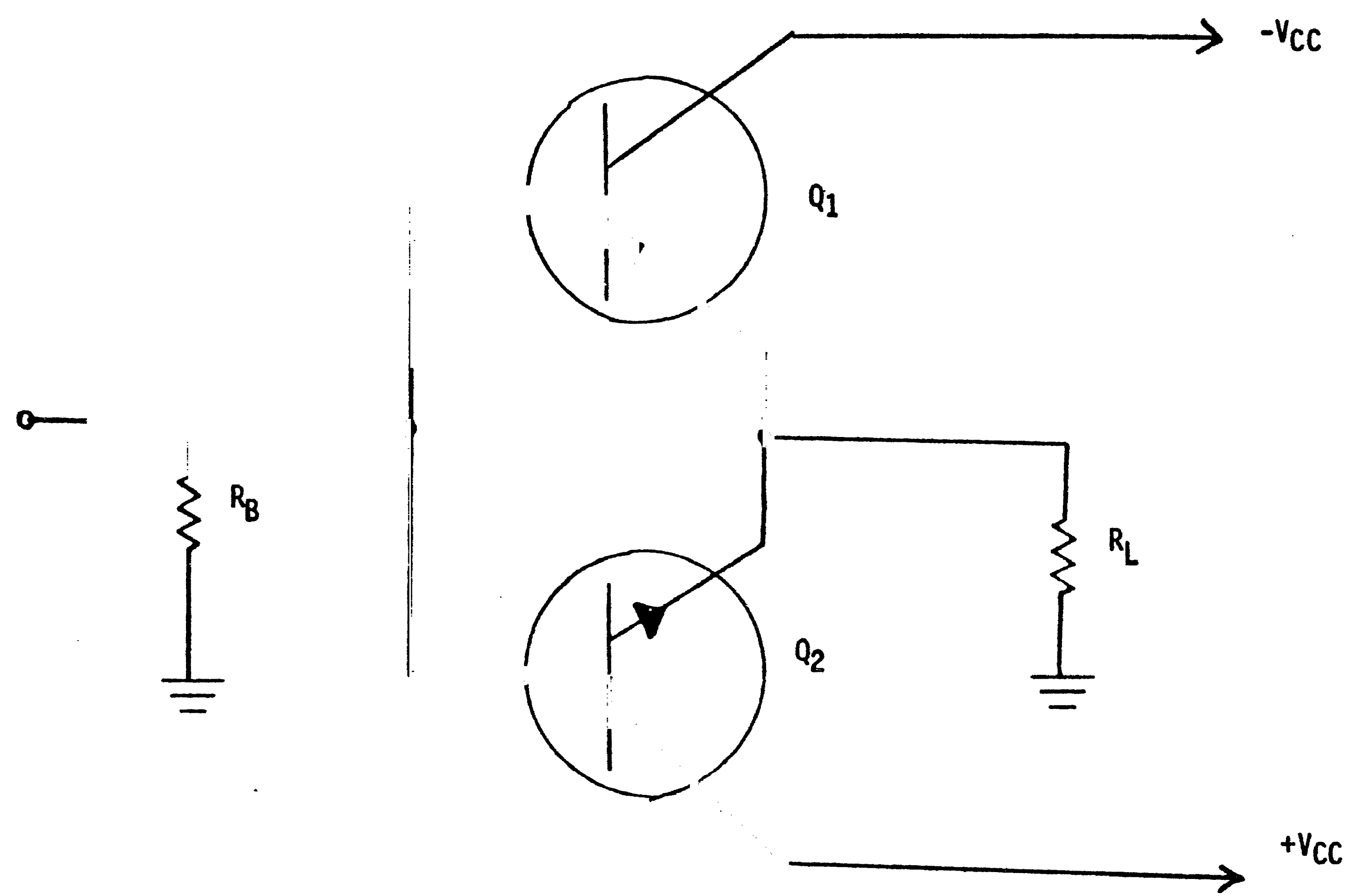
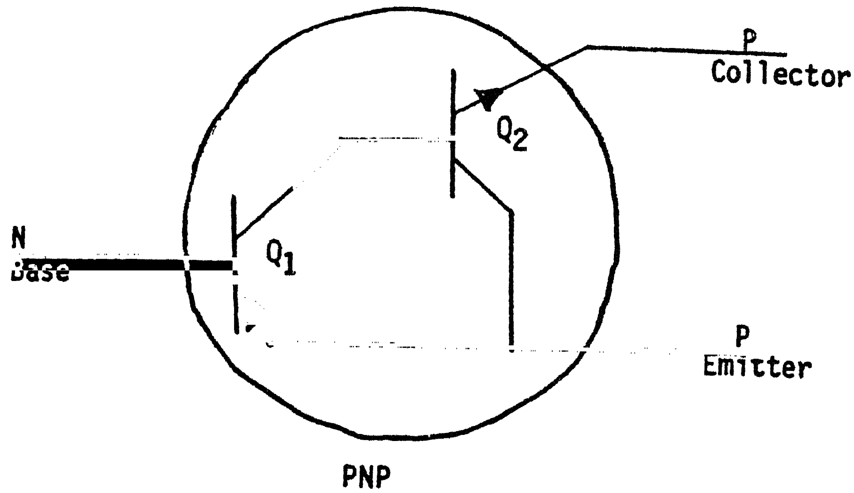


Figure 1 - Complementary Symmetry



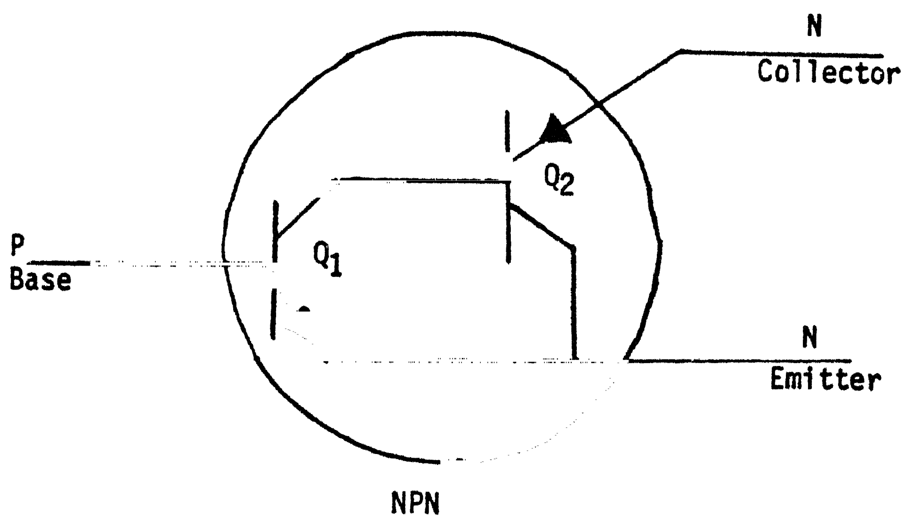


Figure 2.-Complementary Darlingtons.

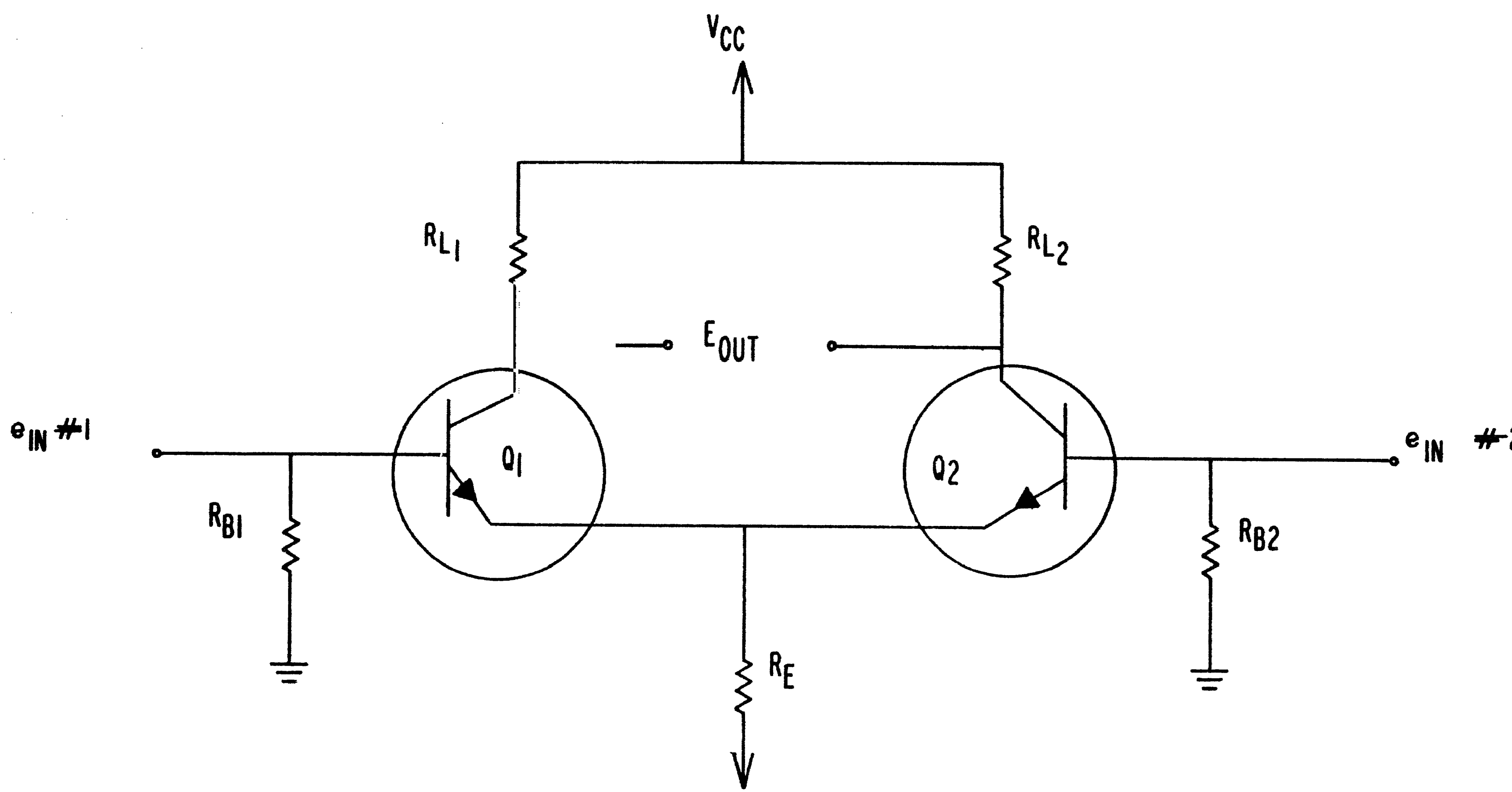


Figure 3.-Two-Input-Balanced Output Differential Amplifier

II. Operational Amplifiers

A. Definition

B. Uses

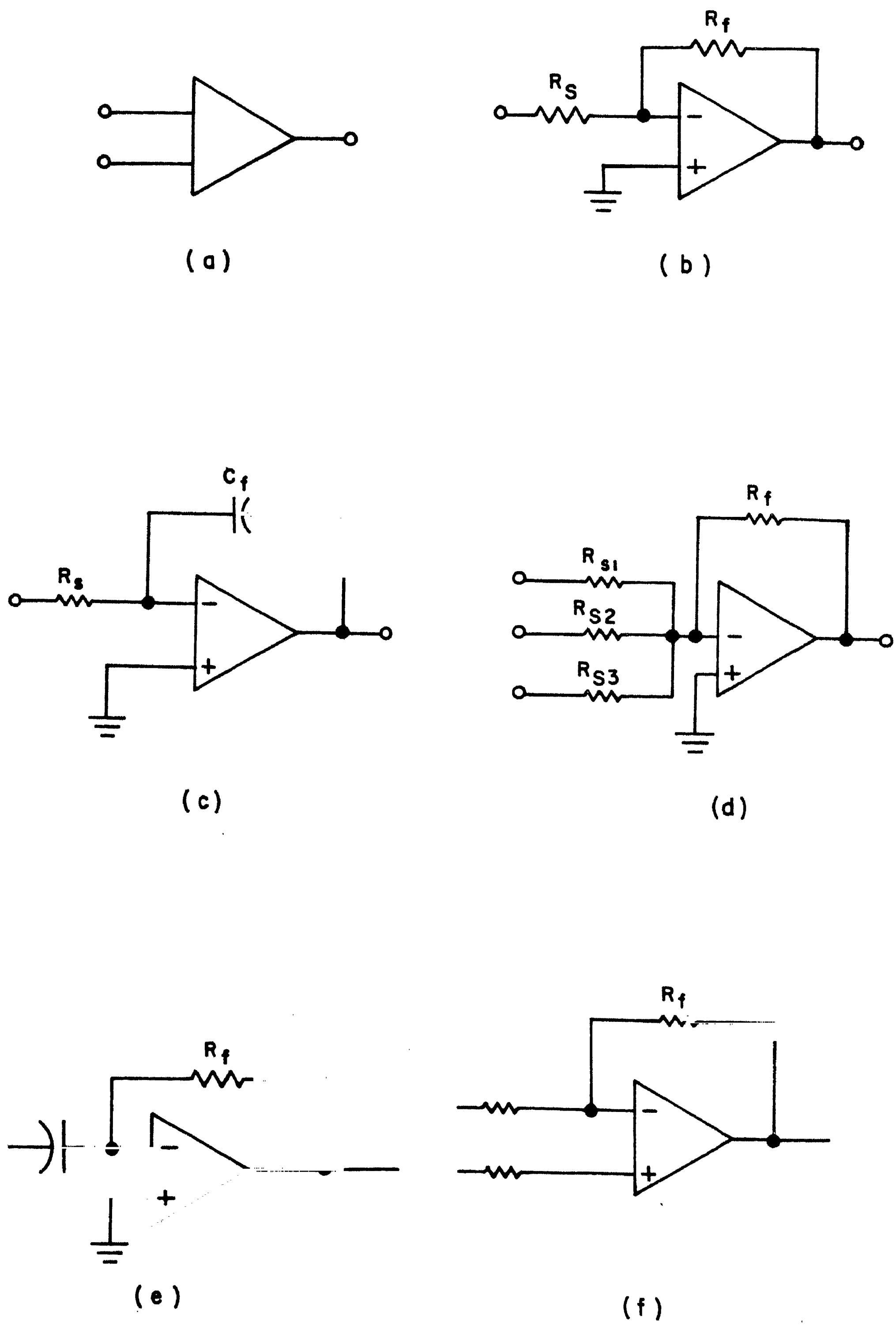


Figure 4.-Operational Amplifier

C. Schematic symbol

D. Basic functional analysis

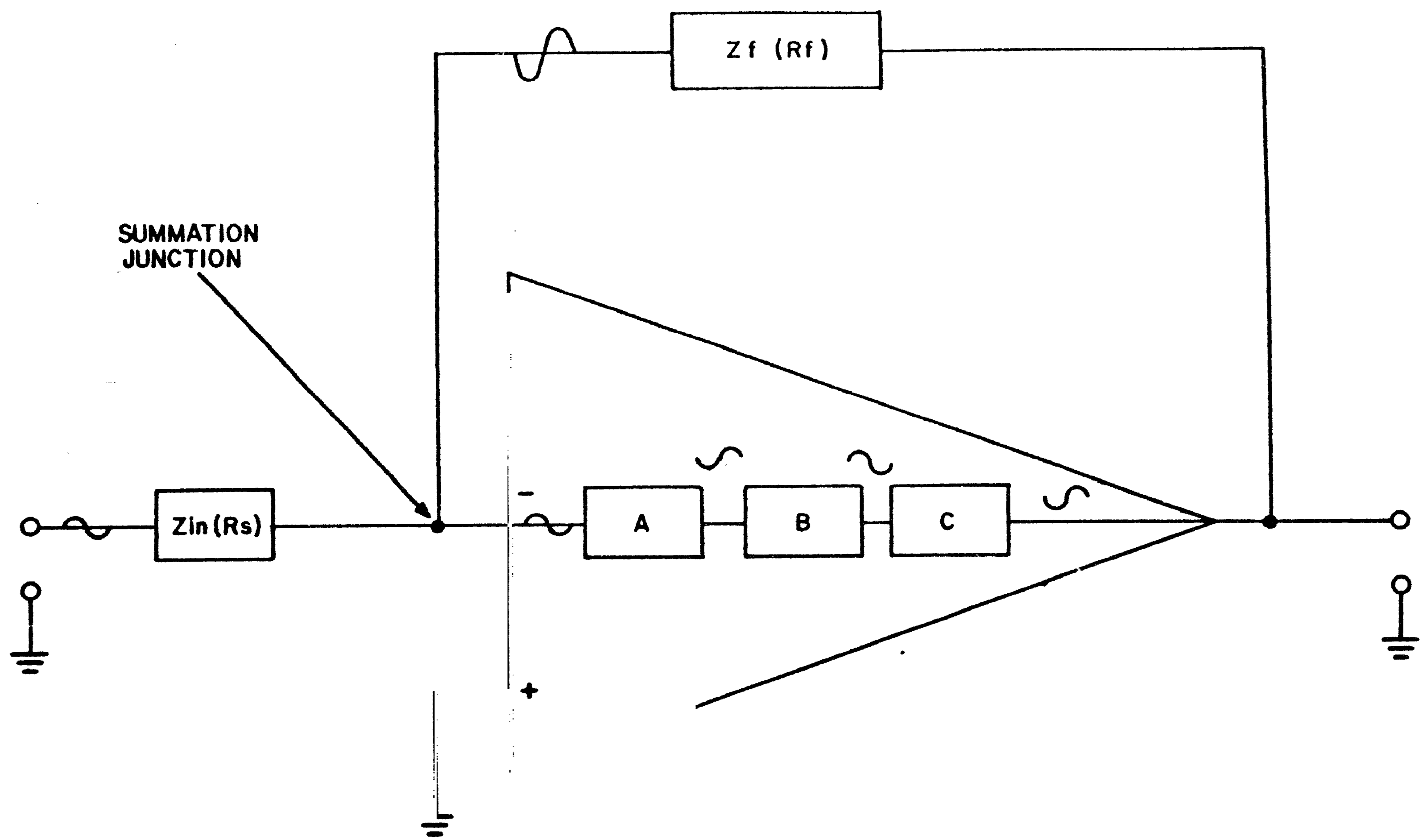


Figure 5.-Op-Amp and Feedback Circuit

E. Differential amplifier

1. Use

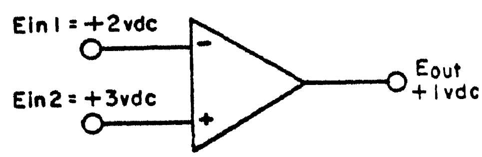


Fig. 3 DIFFERENTIAL AMPLIFIER (basic)

Figure 6

2. Impedance ratio

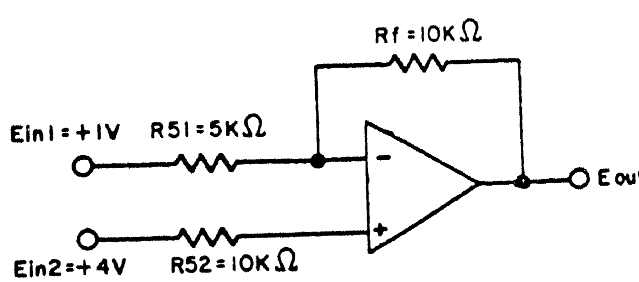


Fig. 4 DIFFERENTIAL AMPLIFIER

Figure 7

INFORMATION SHEET 2.13.1I

TRANSFORMER COUPLED AMPLIFIERS

INTRODUCTION

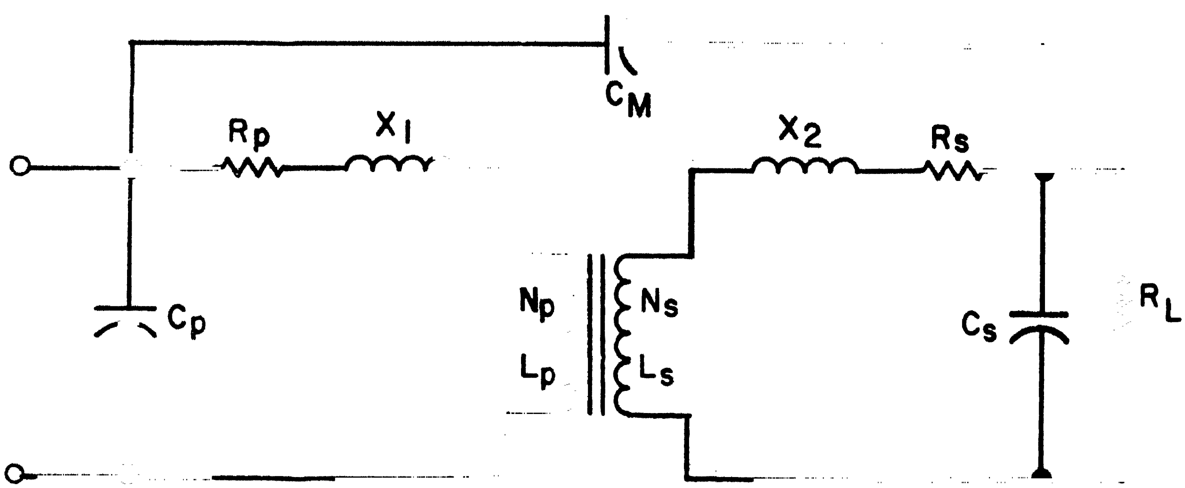
Many electronic systems, ranging from voltage regulators to complex instrumentation systems, require the amplification of d-c and a-c voltages. Many times one stage of amplification is not sufficient to brig the amplitude of such signals to the required values; therefore, the different types of coupling are necessary to ensure that maximum transference of energy is required. This lesson on transformer coupling is essential for the technician.

REFERENCES

1. Milton S. Kiver, Transistor and Integrated Electronics. McGraw-Hill Book Company, Fourth Edition, 1972.

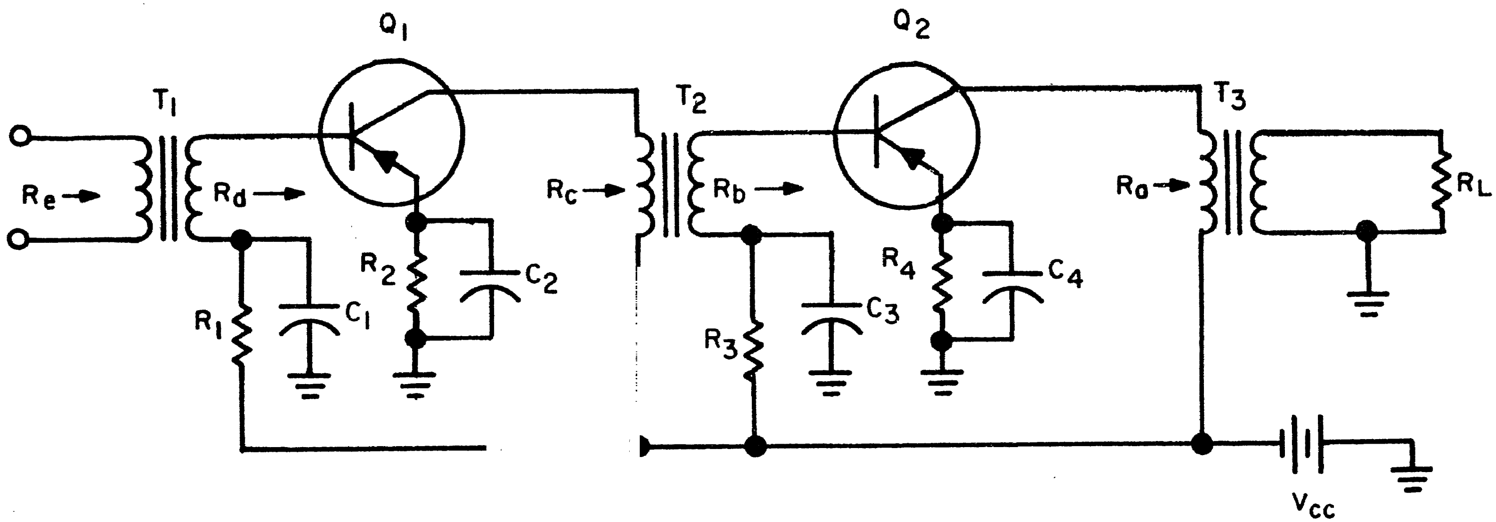
2. Robert L. Shrader, Electronic Communication, McGraw-Hill Book Company, Fourth Edition, 1980.

INFORMATION



TRANSFORMER EQUIVALENT CIRCUIT

Figure 1



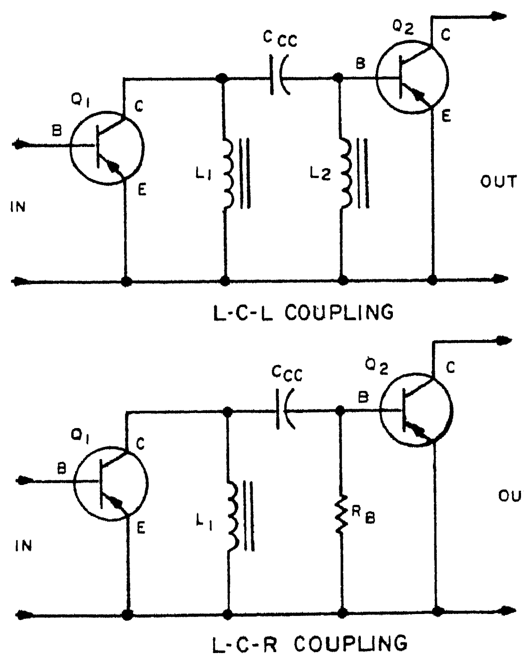
TRANSFORMER-COUPLED TRANSISTOR AMPLIFIER

Figure 2

I. Transistor circuits

A. General

1. Impedance coupling--The impedance coupler is used extensively in the transistor field. Here the increased power-handling (and matching) capabilities of an inductor provide more output than the load resistor. While the overall frequency response of impedance coupling is not as good as that of resistance coupling, it is much better than that of transformer coupling, because there are no leakage reactance effects to deteriorate the high-frequency response. The high-frequency response of the impedance coupler is limited mainly by the collector output capacitance, and the low-frequency response is limited by the shunt reactance of the inductor, L1. The efficiency of the impedance coupler is approximately the same as that of the transformer-coupled circuit (50% for the ideal case). See figure 3.



Impedance-Coupling Circuits

Figure 3

2. Transformer coupling--Transformer coupling is used extensively in cascaded transistor stages and power output stages. It provides good frequency response and proper matching of input and output impedances with good power conversion efficiency. It is relatively much more costly and occupies more space

than the simple RC circuit components, but it compares favorably in these respects with the impedance coupler. Its frequency response is less than that of the resistance- or impedance-coupled circuit.

3. Coupling between stages is achieved through the mutual inductive coupling of primary and secondary windings. Since these windings are separated physically, the input and output circuits are isolated for d-c biasing, yet coupled for a-c signal transfer. The primary winding presents a low d-c resistance, minimizing colector current losses and allowing a lower applied collector voltage for the same gain as other coupling methods, and it presents an a-c load impedance of the following stage. The secondary winding also completes the base d-c return path and provides better thermal stability because of the low d-c (winding) resistance. Since the transistor input and output impedance can be matched by using the proper turns ratio, maximum available gain can be obtained from the transistor.

4. As in the impedance coupler, the shunt reactance of the transformer windings causes the low-frequency response to drop off, while high-frequency response is limited by the leakage reactance between the primary and secondary windings, in addition to the effect of collector capacitance. Because of the low d-c resistance in the primary winding, no excess power is dissipated, and the power efficiency approaches the maximum theoretical value of 50%.

B. Transistor impedance-coupled audio amplifier

1. Application--The impedance-coupled transistor audio amplifier is used where higher gain than the RC-coupled stage is desired with better response than that provided by transformer coupling.

2. Characteristics

   a. Uses common-emitter circuit for higher gain.

   b. Operates class A for linear operation and minimum distortion.

   c. Usually amplifies small signals, but can be designed to handle large signals in cascaded stages.

   d. Is fixed-biased from the collector supply, but may use self-bias in some applications.

   e. Emitter swamping is normally used for thermal stabilization.

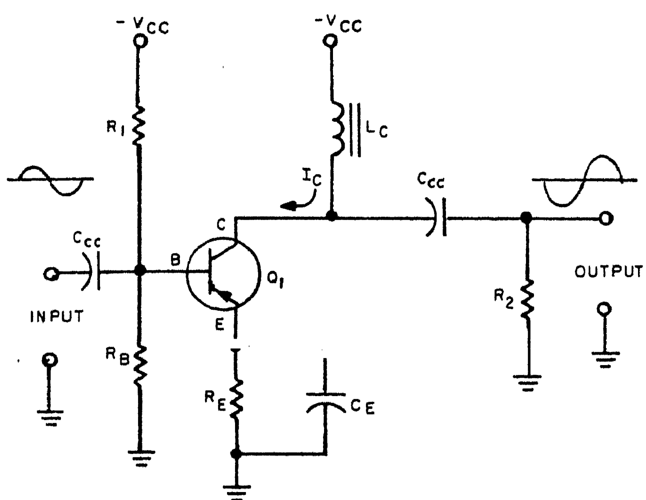
f. Gain is fairly uniform over a range of approximately 100 to 15,000 Hz or more.

g. Both voltage and power gain are high.

3. Circuit analysis

a. The impedance-coupled transistor amplifier is similar in a general sense to the impedance-coupled electron-tube amplifier.

Figure 4 shows a conventional PNP, triode, common-emitter impedance-coupled transistor audio amplifier circuit.



Impedance-Coupled Audio Amplifier

Figure 4

b. The input is shown capacitively coupled, and voltage divider R_1, R_B provides fixed bias form the collector supply. Emitter swamping is provided by R_E for temperature stabilization; R_E is bypassed by C_E. Collector impedance L_C is the load across which the output voltage is developed; this voltage is applied through coupling capacitor C_{CC} to the output circuit. Resistor R_2 is the base-to-ground resistor in the next stage when cascaded amplifiers are used, or is the output load resistor (such as a headset) in a single-ended stage. (In some applications, R_2 may be replaced by an iron-cored inductor similar to L_C.

c. Normally, the amplifier is a small-signal amplifier with the bias fixed at the center of the transistor dynamic transfer characteristic. With no input signal, a steady collector current I_C flows as determined by the base bias voltage. With R_2 and R_B connected across the collector supply as a voltage divider, a forward (negative) bias is developed across R_B; this bias is sufficient to cause the quiescent value of I_C to flow, even though the collector is reverse-biased.

d. When the input signal goes positive, assuming a sinewave iput, the forward base bias is decreased instantaneously by the amplitude of the input signal, and collector current I_C is reduced. The reduction in collector current causes the voltage across collector impedance L_C to decrease and rise toward the supply voltage, which is negative; thus, a negative-swinging output signal is developed. When the input signal becomes negative, it adds to the forward base bias and causes I_C to increase. The increase in collector current through L_C produces a large voltage drop across the impedance, reduces the negative collector voltage, and produces a positive swing. Therefore, the collector output follows the input signal except that it is reversed in polarity; when the input signal is positive, the output signal is negative, and vice versa. The collector output is developed across the impedance of L_C between the collector and ground, and is applied through coupling capacitor C_{CC} to the base of the next stage, or to the output load.

e. In cascaded impedance-coupled stages, the base bias resistor and base-to-emitter internal impedance of the next stage transistor offer a shunt path between coupling capacitor C_{CC} and ground. Therefore, the reactance of C_{CC} and the total parallel resistance (or impedance) from resistor of the first stage. If the reactance of the coupling capacitor is large, the output voltage is greatly attenuated, and ony a small output appears between base and ground of the second stage. Since the reactance of C_{CC} varies inversely with frequency, the lower audio frequencies are attenuated more than the higher frequencies. For good low-frequency response, the coupling capacitor is made sufficiently large in value that its reactance is very small as compared with the base-to-ground resistance or impedance. This is similar to vacuum-tube practice, where relatively small coupling capacitors (such as .001 μF) are satisfactory, because the vacuum-tube grid-to-ground

impedance is very high. Because the transistor base-to-emitter impedance is fairly low (about 500 ohms), a coupling capacitor of 50 μF or more is needed to achieve the low impedance required to pass the signal without excessive attenuation. (A 50μF capacitor has a capacitive reactance of approximately 50 ohms at 100 Hz). For good low-frequency response, the reactance of the coupling capacitor should always be less than one-tenth the effective base input impedance.

f. In those circuits where an impedance replaces R_2, the coupling capacitor and inductor can be made to series-resonate at a low frequency to provide base boost. At the higher audio frequencies (about 15,000 Hz), the collector-to-emitter shunting capacitance of the second stage, together with the large distributed capacitance from turn to turn of the collector-inductance, tend to bypass the high frequencies to ground, causing a drop in the response.

g. The frequency-attenuating action produced by the transistor occurs because the width of the internal transistor PN junctions is voltage-sensitive. With higher voltage, the transition region is narrow, corresponding to the closely spaced plates of a capacitor with the associated high capacitance. The reverse bias on the collector also reduces the width of this transition region, so that transistors are generally characterized by a high inter-electrode capacitance. For example, an audio transistor may have a collector-to-base capacitance on the order of 50pF, as compared with a vacuum-tube plate-to-grid capacitance of one or more pF. The collector-to-emitter capacitance is usually 5 to 10 times the value of the collector-to-base capacitance (in the common-emitter circuit), as compared with 8pF or less for vacuum-tube plate-to-cathode capacitance. Thus, it can be seen how the high-frequency response is affected considerably by internal transistor parameters. Of course, any shunt wiring capacitance and that of the collector inductance will also add to the shunting effects of the transistor. Both low-and high-frequency compensating circuits may be used to increase the frequency response of the circuit.

h. Over the region of 100 to 15,000 Hz, the impedance-coupled amplifier has a relatively flat response, and with proper matching will afford high power and voltage gains. Hence, this form of coupling is employed where good audio response is required with a moderate power output (for high output,

transformer-coupling is used). The common-base configuration is sometimes employed where better high-frequency response is desired than that provided by the common-emitter circuit, since the collector-to-base capacitance is only 1/5 to 1/10 as great.

i. Transistor audio amplifiers are also characterized by a high inherent noise which is greatest at the lower audio frequencies. Operating with low values of emitter current and low collector voltages, together with low values of input resistance, tends to minimize the noise. By using an inductor in place of the base-to-ground resistor (R_B or R_2 in the schematic), a very low input resistance, and a lower noise figure over that of the RC-coupled amplifier, is obtained. In the common-emitter, degenerative effects produced by an unbypassed emitter resistor tend to increase the input resistance. Thus, it is conventional practice to use large emitter bypass capacitors to avoid any possibility of degeneration. As with electron tubes, external feedback circuits provide better response, although emitter degeneration may sometimes be used. Since fixed bias from the collector supply may be easily obtained by a simple voltage divider, it is used in both large-and small-signal applications. Self-bias is generally restricted in use to very small-signal amplifiers; otherwise, distortion and improper operation with a reduction in gain, or blocking, may occur on large signals. The emitter resistor functions mainly as a swamping resistor for temperature stabilization, and prevents large changes in amplification with temperature variations.

j. In considering the operation of the transistor impedance-coupled amplifier as compared with the electron-tube impedance-coupled amplifier, it should be clear from the above discussion that one circuit is an almost exact counterpart (dual) of the other. The difference is that transistor stages operate with low input and output impedances, at low voltages, and at very low levels of amplification, whereas electron-tube stages operate with relatively high input and output impedances, at high voltages, and at high levels of amplification. Thus, the transistor is basically a current amplifier, while the electron tube is a voltage amplifier. Consequently, the transistor requires closer matching (rather than mismatching) of impedances to maximize performance.

C. Transistor transformer-coupled audio amplifier

1. Application - The transformer-coupled transistor audio amplifier is used where higher gain and power output than that provided by an RF-coupled or impedance-coupled stage are required, and where the reduction in frequency response can be tolerated.

2. Characteristics

   a. Uses common-emitter circuit for higher gain.

   b. Operates class A for linear operation and minimize distortion.

   c. Usually amplifies small signals, but can be designed to handle large signals in cascaded stages.

   d. Is fixed-biased from the collector supply, but may use self-bias in some applications.

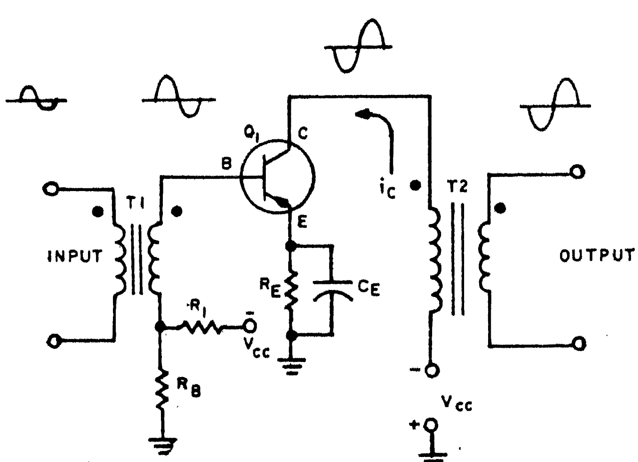
   e. Emitter swamping is normally used for thermal stabilization.

   f. Gain is fairly uniform over a range of approximately 100 to 10,000 Hz or more.

   g. Both voltage and power gains are high.

3. Circuit analysis

   a. The transformer-coupled transistor amplifier is similar in general to the transformer-coupled electron-tube amplifier. See figure 5.



Transformer-Coupled Audio Amplifier

Figure 5

b. Circuit operation--The accompanying schematic is that of a conventional PNP, triode, common-emitter, transformer-coupled transistor audio amplifier circuit. The input is shown transformer-coupled through T1, and voltage divider R_1, R_B provides fixed bias from the collector supply. Emitter swamping is provided by R_E for temperature stabilization; R_E is bypassed by C_E. The output is transformer-coupled through T2.

c. The use of T1 to apply the input signal to the base circuit provides an almost ideal temperature response characteristic. The low transformer winding resistance produces a low base input resistance and, when used with emitter swamping resistor R_E, any variation in gain with temperature is reduced to a very small value over a large range of temperatures (greater than for any other type of coupling circuit). Normally, transistor Q_1 rests in its quiescent condition, with class A bias provided by voltage divider R_1, R_B. The quiescent collector current, I_C, is steady, producing only a small constant voltage drop across the primary resistance of T2. Thus, practically the full value of collector supply, V_{CC}, is available. With a steady collector current, no voltage is induced in the secondary of T2, and there is no output (assuming no input signal or noise). When a positive-swinging signal is introduced into the input circuit, current flow through the primary of T1 induces a voltage in the secondary, which is applied to the base of Q1. Assuming that the transformer secondary is connected in-phase with the primary, a positive increase in voltage appears at the base. This positive voltage swing cancels the forward negative bias, and a reduced flow of collector current occurs. As the instantaneous collector current decreases, the primary voltage drop also decreases, and allows the collector voltage to rise toward the negative supply voltage. Meanwhile, the reducing collector current induces a voltage in the secondary winding. The secondary winding is connected in-phase so that a reducing collector current produces a negative voltage swing in the secondary, and an increasing current produces a positive swing. The emitter current flowing through R_E is the steady quiescent value, and any change in base bias with input signal is bypassed around the emitter resistor through capacitor C_E. Although the capacitor will not pass the quiescent d-c current, it will pass the alternating audio voltage produced by the changing input signal. Thus, only d-c current changes flowing through R_E (the thermally induced changes caused by temperature variation) produce an emitter bias.

This emitter bias is in a direction which causes a reduced flow or emitter current, since it reduces the forward bias and hence reduces the collector current back to the original value so that it appears unchanged. If the emitter bypass capacitor were not used, the input signal voltage would produce a degenerative effect, since all collector and emitter current would be forced to flow through the emitter resistor.

d. Consider next the next negative swing of the input signal. In this instance, the forward bias on the base element is increased (the two negative voltages add), and a heavy collector current flow occurs. The increasing I_C through the primary of T2 induces a voltage into the secondary. Assuming the same in-phase connection of the primary and secondary, the output voltage is positive. By changing the connections of the secondary winding of either T1 or T2, the signal can be changed so that it is of the same phase at both the input and the output; this is an advantage of transformer coupling.

e. Since the secondaries of T1 and T2 are not connected to their primaries, the transformers offer a convenient method of separating input or output signals from bias or collector voltages. By using the proper turns ratio, the primary and secondary impedances may be matched. In the base circuit, the input resistance is matched, giving maximum gain; likewise, in the output circuit, the proper turns ratio reflects the secondary load impedance into the primary, which, when added to that of the transformer primary itself, provides a matched load for maximum output.

f. Normally, the transformer-coupled stage is operated in the middle of its transfer characteristic to produce linear amplification. It is also a small-signal amplifier when used in preamplifier stages. In following cascaded stages, it becomes a large-signal amplifier, operating with a larger bias over the linear range of its transfer characteristic. When necessary, bias resistor R_B is bypassed to ground with a large capacitor to prevent audio signal voltages from causing the bias to change with the signal, particularly in high-gain and large-signal amplifiers.

g. In cascaded transistor amplifiers, the load on the secondary of T2 is the base resistance of the next transistor. Since this is resistive rather than reactive, there is less frequency distortion than would occur in an electron tube, where the load is predominately reactive (even in output stages, the speaker is a varying reactance). In low-power stages, the flow of reverse (leakage) current, I_{CEO}, through the collector-to-base junction becomes important when it is a large percentage of the total operating collector current. Thus, the designer chooses a transistor with as large a beta as is possible, and as small a leakage current as can be obtained, in order to get the most gain with the least leakage current. (The flow of reverse current does not occur in electron tubes.)

h. The frequency response of the transformer-coupled amplifier is lower than that of the resistor-coupled or impedance-coupled transistor audio amplifier. There is more shunting capacitance than in resistance coupling because of the transformer distributed turn capacitance, and there is a leakage inductance between the primary and secondary which does not exist in the impedance-coupled stage. The primary inductance is usually made from 2 to 5 times load resistance, R_L, for good low-frequency reponse. However, the lower the frequency, the less the inductive reactance, so that the response tends to drop at low frequencies. The high-frequency response is primarily determined by the combination of shunting capacitance with load resistance and linkage inductance, while the low-frequency response is detrmined by the combination of load resistance and magnetizing inductance. In addition, the shunting capacitance and inductance form resonant circuits which produce humps in the response curve. Practically speaking, the response is very similar to that of the electron-tube transformer-coupled audio stage, with somewhat less high-frequency response. Loss of low-frequency response as compared with the electron-tube circuit becomes apparent when miniaturized transformers are used, because of the difficulty of building transformers with a sufficiently large iron core to provide a high inductance with the limited number of turns available in the space allocated.

i. Despite the apparent loss of response in the transistor transformer-coupled amplifier as compared with other forms of coupling and the use of electron tubes, relatively good response is obtained by using more stages and low- and high-frequency peaking circuits where necessary. A maximum efficiency of about 50% is obtained as compared with 25 to 30% for resistance-coupled stages.

NOTETAKING SHEET 2.13.1N

TRANSFORMER-COUPLED AMPLIFIERS

REFERENCES:

1. Milton S. Kiver, Transistor and Integrated Electronics. McGraw-Hill Book Company, Fourth Edition, 1972.

2. Robert L. Shrader, Electronic Communication, McGraw Hill Book Company, Fourth Edition, 1980.

3. Programmed Instruction, Transformers, M135.

NOTETAKING OUTLINE

I. Advantages/Disadvantages

II. Transformer Theory

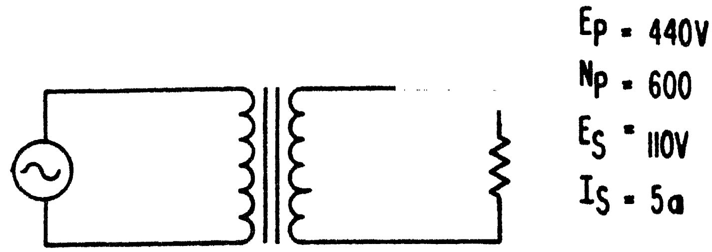


Figure 1

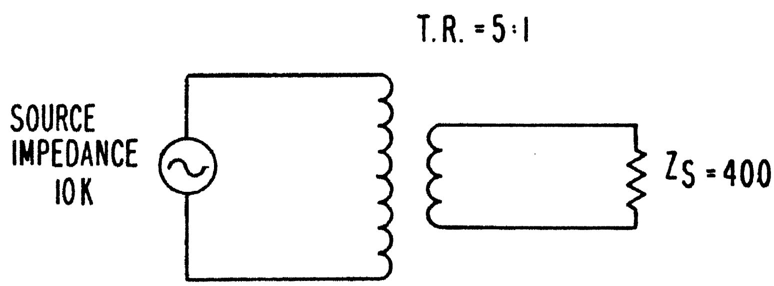


Figure 2

III. Frequency Response

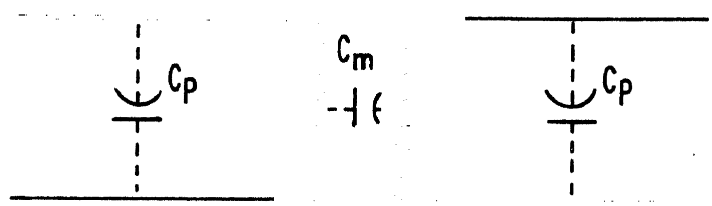


Figure 3.- Distributed Capacitances in Transformers.

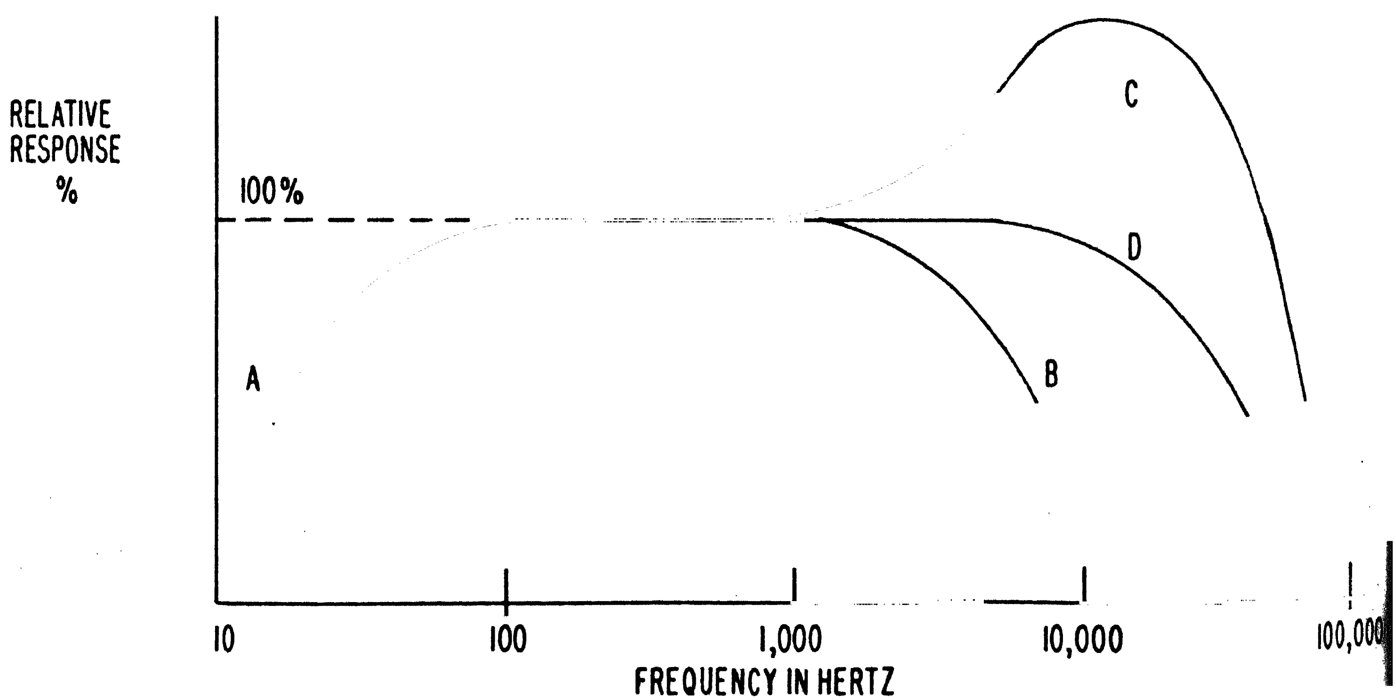


Figure 4.- Frequency Response of a Transformer.

INFORMATION SHEET 2.14.1I

SPECIAL DEVICES

INTRODUCTION

Ever since the development of solid state devices, the ability of a crystal to amplify or control has been under constant investigation. Manufacturers have been forming layers of semiconductor materials, inserting PN junctions, shaping new geometries, and varying doping levels in the search for new control or amplifying devices. Some of the newly made special devices parallel transistor characteristics; while other devices completely take over functions that a transistor cannot perform. At the present "state-of-the-art", several devices will be explained in this information.

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2. Milton S. Kiver, Transistor and Integrated Electronics. McGraw-Hill Book Company, 1972, Fourth Edition.

3. Anthony S. Manera, Solid State Electronic Circuits: for Engineering Technology, McGraw-Hill Book Company, Inc., 1973.

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INFORMATION

I. BASIC CONSTRUCTION AND OPERATION OF JFET

A. JFET Construction

1. The Junction Field-Effect Transistor (JFET) is a solid-state device with a very high input impedance and a high output impedance--two favorable attributes also found in vacuum tubes. Like a vacuum tube, the JFET is a voltage-controlled device. (The conventional transistor is a current-controlled device.) In its operation and construction, the JFET is completely different from a vacuum tube, yet many circuits of both are very similar. The JFET is a semiconductor device with no filament, so no excess heat must be dissipated. It may be operated at high voltages comparable to those of small vacuum tubes, or with the low voltages normally used with transistors.

2. The JFET is linear in much of its range of operation. This permits the designing of low distortion circuits that have a minimum of cross modulation. Low noise is another favorable feature of the JFET.

3. The usable range of a JFET extends from very low frequencies into the UHF spectrum. In addition to their use as small-signal high frequency amplifiers, JFETs are popular as small-signal mixers and oscillators. They also are used in small-signal audio and video amplifiers. A few high-power junction field-effect transistors are available with high current capabilities. As the demand rises and production techniques improve, higher power JFETs will be marketed.

4. Like most solid-state devices, field effect transistors are temperature sensitive, but not as much as conventional (bipolar) transistors. Input and output capacitances of the FET are moderate. Both temperature and capacitance problems are reduced when appropriate external circuit designs are used. JFETs can be destroyed quickly if maximum ratings are exceeded. As in the production of many solid-state devices, there are wide variations in units of the same type, so performance specifications are not too strict. This limitation also can be compensated for by proper external circuit design.

5. The simplified JFET structure shown in figure 1 is helpful in obtaining a fundamental understanding of JFET operation. First imagine simple bar of N-type material with direct (ohmic) contacts at each end; excess electrons are available in the material. A voltage source connected across the leads, causes a movement of electrons. The magnitude of the electron flow depends on the applied voltage, the amount of doping, and the dimensions of the semiconductor bar. Of course, the larger the cross-sectional area of the bar, the lower the resistivity. Likewise, the greater the doping of the N-type material, the lower the resistivity.

6. It is not feasible to vary the physical dimensions of the bar or its doping level; however, it is possible to influence the movement of charges by changing the resistivity of the bar. This can be done electrically by varying the depletion region.

7. The connection of a voltage source between the leads
igure 1A) sets up a voltage gradient along the bar of
-onductor material. The voltage at a given point
es more positive as one proceeds along the bar
the negative to the positive side.

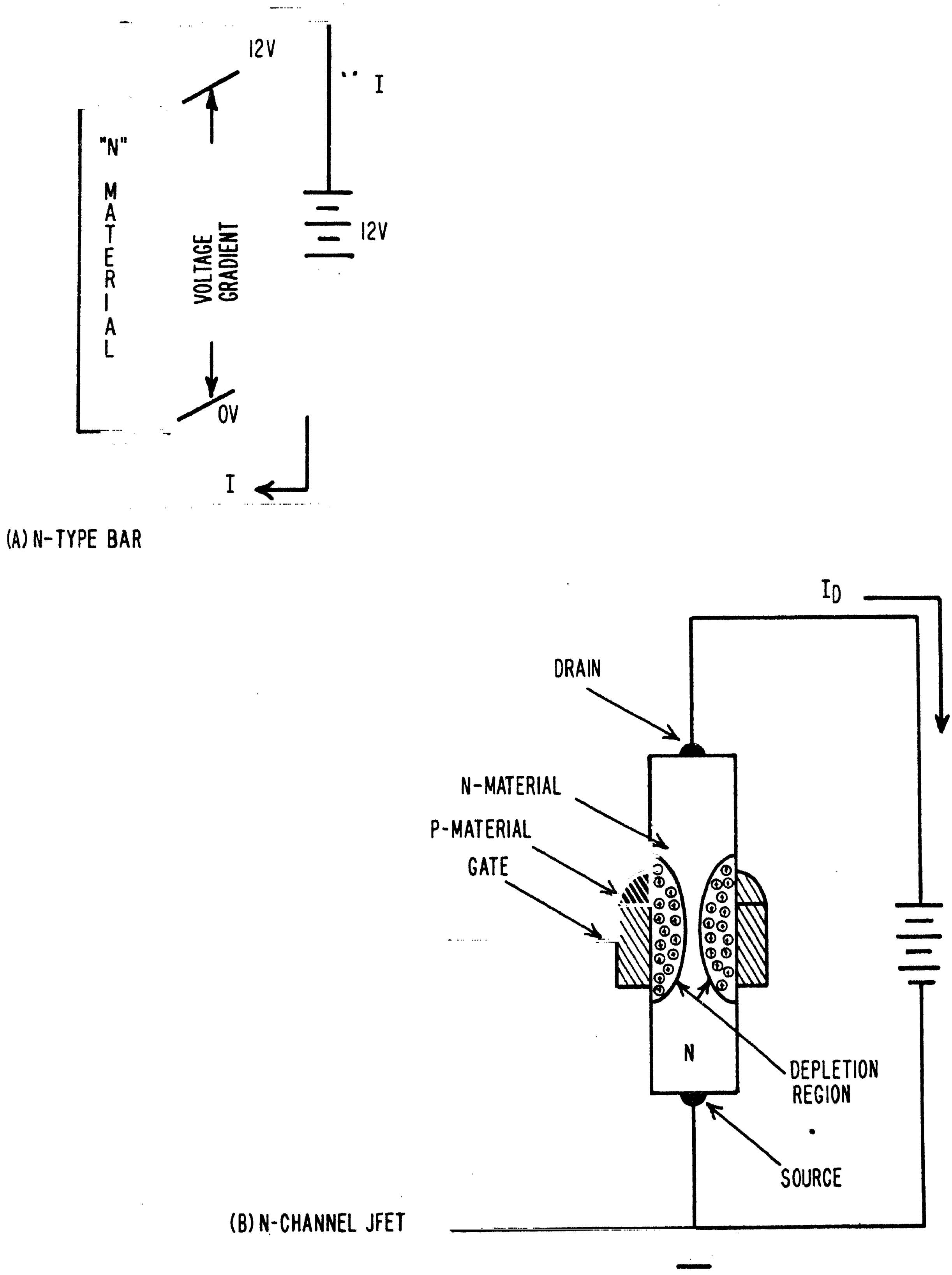


Figure 1 Basic JFET Structure.

8. In the structure shown in figure 1(B), a P-type material is wrapped around the N-type bar, forming a PN junction. The junction is biased by connecting the P-type material to the negative side of the bar. A reverse bias on the junction is obtained because of the positive gradient that extends from the common end of the bar to the positive end.

9. In previous lessons, the influences of a reverse bias on the depletion regions associated with a PN junction were detailed. It is this activity that is able to control the movement of charges through the bar. In JFET terminology the bar is called a channel. (Therefore, figure 1(B) is an N-channel JFET). The element that controls the motion of charges along the channel is called the gate. The common end of the channel and its associated lead is known as the source, while the opposite end of the channel and its associated lead is called the drain. The gate can be compared to the control grid of a vacuum-tube--the source and drain can be compared to the cathode and plate respectively.

B. Influence of the Reverse-Biased Junction

1. A reverse-biased junction causes the development of a depletion region in the channel, as shown in figure 2. Adequate doping keeps the resistivity of the gate material lower than that of the channel material.

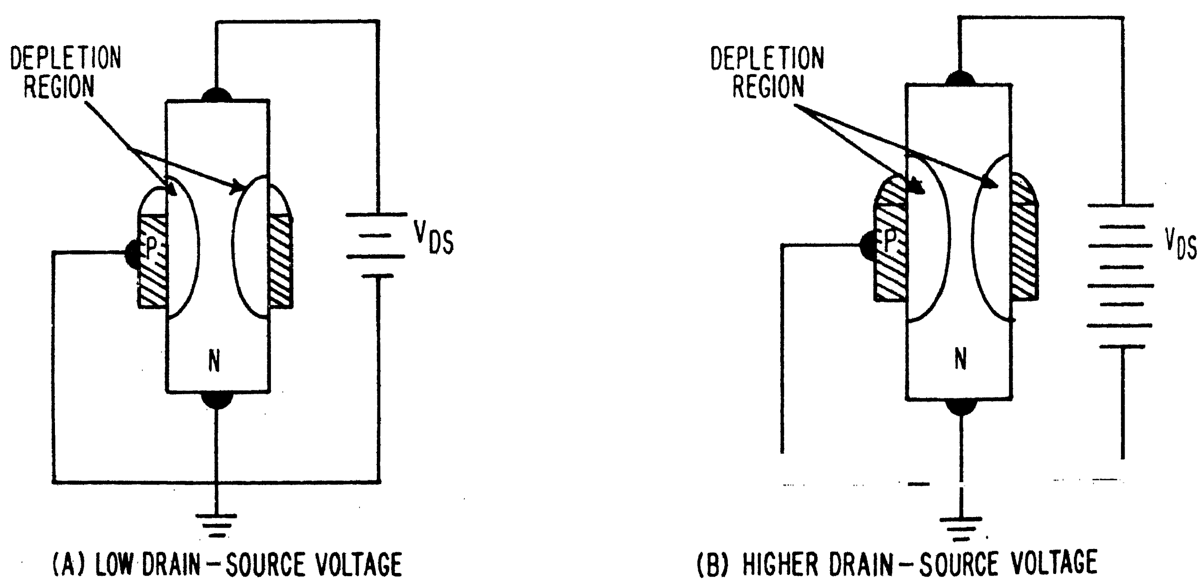


Figure 2 Influence of Drain-Source Voltage on Depletion Region and Current

Thus, the depletion region extends into the channel much farther than into the gate material. (The depletion region of the latter can be neglected in considering the operation of the field-effect transistor.) The channel depletion region is wedge-shaped because of the voltage gradient rising toward the drain (figure 1(A)).

The presence of the depletion region in the channel causes an increase in the resistivity of the bar. If the drain-source voltage (V_{DS}) is increased, the depletion region extends farther into the channel, increasing its resistance. In figure 2(B) the depletion region would seem to extend through the channel in such a manner that channel current would be stopped or "pinched off."

There are, however, counteracting influences that prevent the complete pinch-off of the current. Increasing V_{DS} tends to increase the current, while a larger depletion region tends to reduce it; thus, current is not stopped. The combined influence of the depletion region and the voltage drop establishes a condition in which the current rises to a maximum and then holds steady (no further increase in channel current with an increase in V_{DS}). This is indicated by the curve in figure 3.

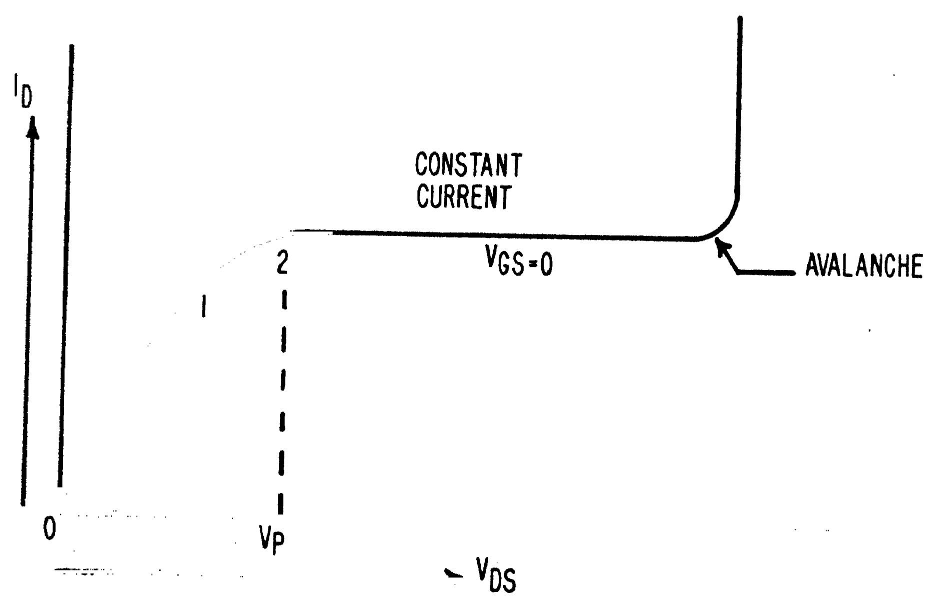


Figure 3 Drain-Source Voltage (V_{DS}) Versus Drain Current (I_D)

4. Between the origin and point 1 on the curve the drain current (I_D) in the channel rises with an increase in the drain-source voltage (V_{DS}). Between points 1 and 2 in the depletion region begins to exert an influence, and the rate of current rise is no longer linear with respect to the increase in the drain-source voltage.

   Point 2 corresponds to full penetration of the channel (where the two depletion regions meet). This is the pinch-off condition. Operation now is in the constant current region where the drain current remains at the same level despite the increase in V_{DS}.

5. If the drain-source voltage is made too high, the gate-channel junction will undergo avalanche breakdown, causing the current to rise sharply. It is possible that the device will be damaged if power dissipation is not held to a safe level.

C. Influence of the Gate Potential

1. The resistivity of the channel depends on both the drain voltage and gate voltage. The influence of the gate on the channel current can be enhanced by connecting a negative voltage between the gate and the source (common), as shown in figure 4. This d-c bias establishes a larger depletion region and increases the channel resistivity for a given V_{DS}. In effect, it will cause pinch-off at a lower V_{DS}. This means that the limiting drain current will also be lower. If the gate bias voltage is made high enough, the channel current can be reduced practically to zero. This activity can be compared with the cut-off of a vacuum tube's plate current when a high control grid bias is applied.

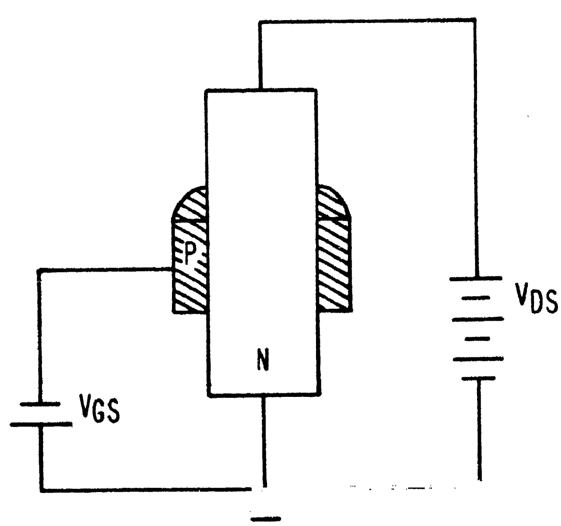


Figure 4 Biasing the Gate-Source Junction

2. Using various values for the gate bias it is possible to establish a family of curves, as shown in figure 5. Note that pinch-off current decreases with an increase in the gate-source bias. The family of curves resembles that of pentode vacuum tubes in appearance.

There are three main regions. In the ohmic region the drain current rises significantly with the increase in the drain-source voltage because neither gate potential nor the channel IR drop have enough influence to cause pinch-off. The drain-source voltage has a significant influence on the drain current, and the output resistance is relatively low. The second region (pinch-off), is one of saturation. The current remains essentially constant for a large change in V_{DS}. This constant current characteristic means that the output resistance is high, providing favorable operating conditions when high voltage and/or power gain are desired. The third region is the breakdown (avalanche) region.

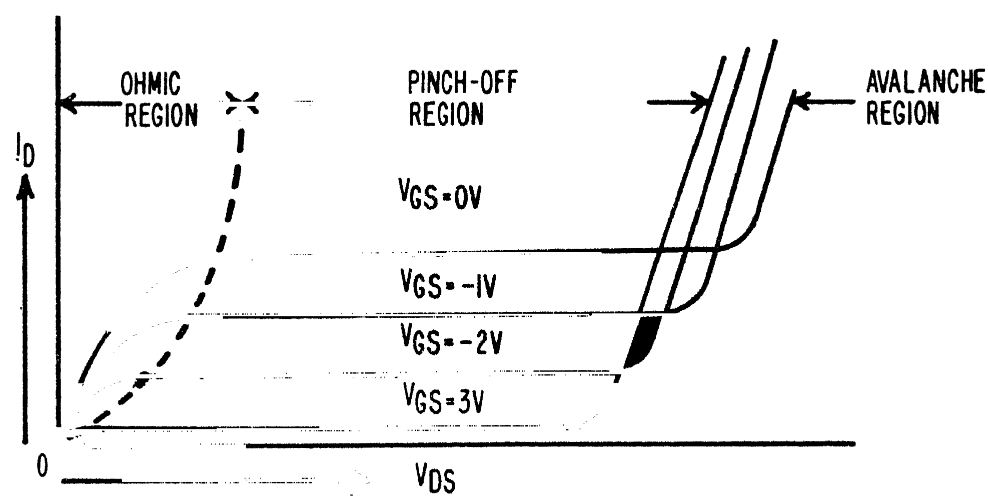


Figure 5 Family of Curves for a Typical N-Channel JFET

3. As long as the gate-channel junction is reverse biased, there is little gate current, consequently, the input impedance is high. Typical values are 10^6 ohms for germanium FET's and 10^9 ohms for silicon FET's; therefore, the input power required to exercise control is very low. Thus, the FET is a device capable of large voltage, current, and power gains.

4. If an a-c signal is impressed between the gate and source, as in figure 6, the depletion region in the channel will vary with the input signal.

   There will be corresponding changes in the resistivity of the channel and the movement of charges through the channel. Consequently, the drain current will follow the changes in the gate-source voltage (V_{GS}). This control of the channel current (I_D) by V_{GS} is similar tc the influence that a grid voltage has on the motion of the electrons (plate current) between the cathode and the plate of a vacuum tube. To the extent that an input signal voltage across a high impedance controls the output current, a field-effect transistor is more like a vacuum tube than a bipolar transistor.

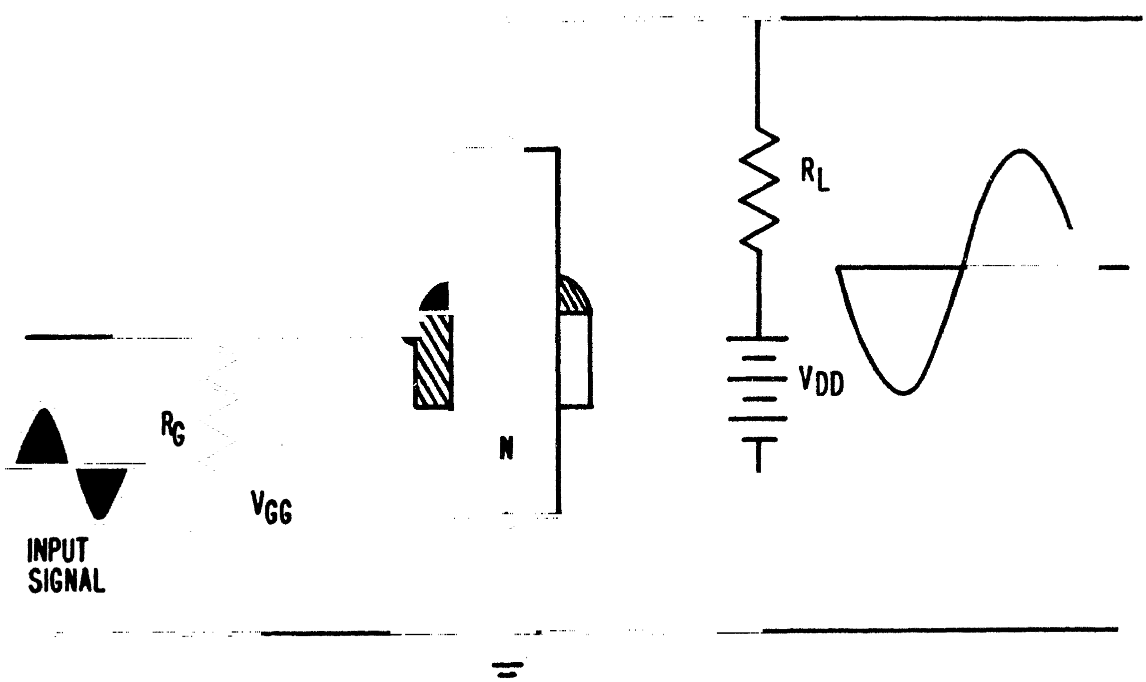


Figure 6 Signal Input to and Output from a JFET

D. JFET Types

1. Field-effect transistors come in various types and structures. Just as there are PNP and NPN junction transistors, there are both N-channel and P-channel JFET's, as seen in figure 7. In a P-channel JFET, the channel is a bar of P-type semiconductor. Current is a result of the flow of positive charges (excess holes). The biasing of the P-channel JFET is opposite from that of the N-channel type, since it requires a negative drain voltage and a positive gate voltage. The field-effect transistor is a unipolar device because there is

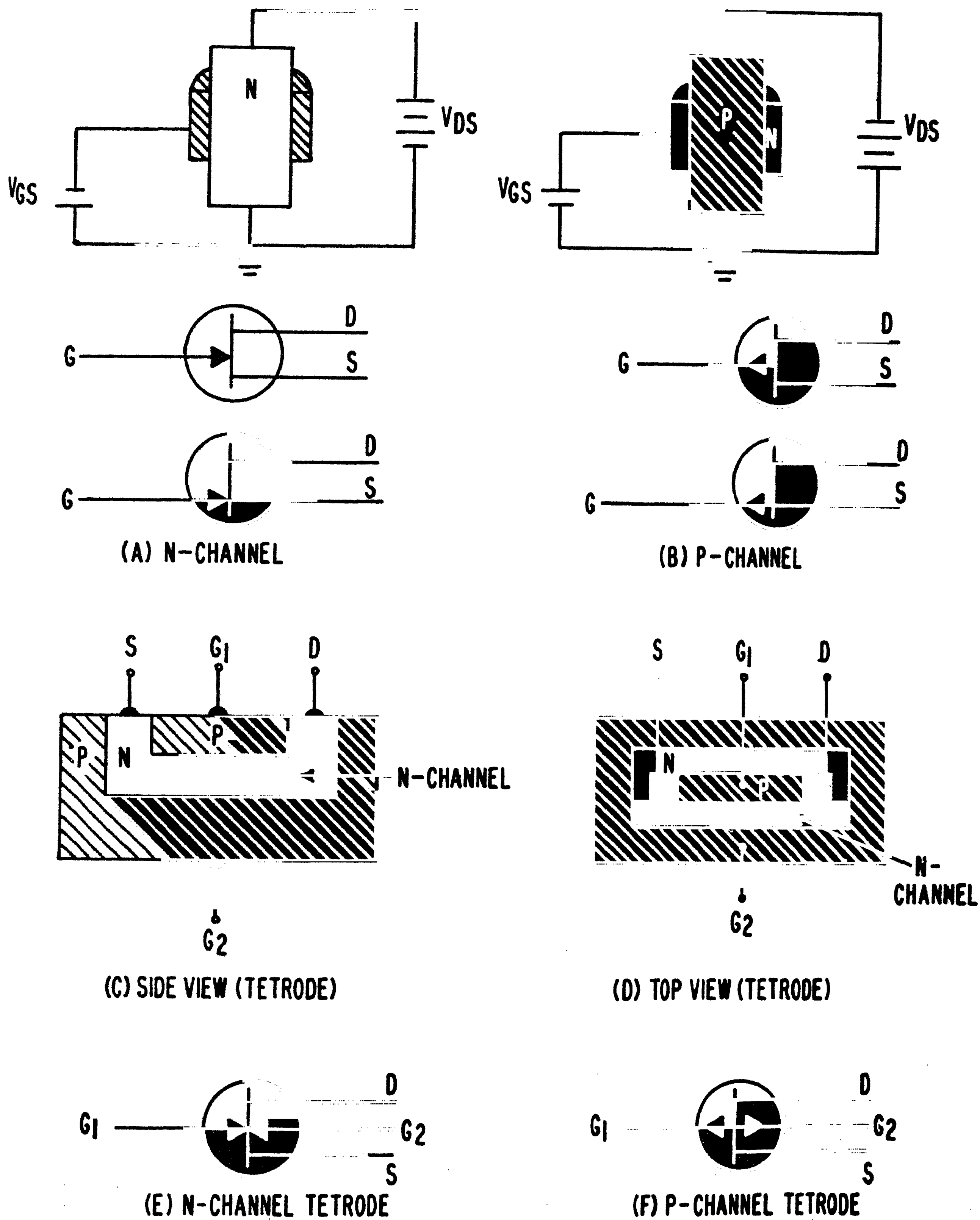


Figure 7 Junction FET's with Symbols

only one type of charge carrier. These carriers in the N-channel FET are electrons, while in the P-channel FET they are holes. The operation of the conventional transistor depends on the motion of both types of charge carriers. For this reason the conventional transistor is called a bipolar type. The bipolar transistor has two junctions, one forward-biased and the other reverse-biased. It is the interaction between electrons and holes at the emitter junction which results in a diffusion current in the base that propels charges into a high electric field across the reverse-biased collector-base junction.

2. It is possible to include two gate elements isolated from each other as shown in figures 7(c) and (d) with their symbols in figures 7(e) and (f). Thus, two inputs are available for mixing and other circuit activities, such as AGC and d-c feedback, in which a d-c control of a-c amplification is to be established. These are called dual-gate field-effect transistors. If the second input is not used, it is normally connected in the circuit so that its gate-channel junction is reverse-biased.

E. Basic Circuit Configurations

1. Like the vacuum tube and the bipolar transistor, the field-effect transistor can be connected in three basic arrangements (figure 8). Each has its individual characteristics. The common-source connection is the most widely used. It has a good voltage gain, a high input impedance, and a medium-to-high output impedance. Input signal is applied between the gate and the source, and the output signal is developed between the drain and the source.

2. Input and output voltages are out-of-phase. For example, a positive swing of the input to an N-channel junction FET increases the drain current through the channel. The resulting increase of drain current through the load resistance causes a decrease in the positive drain voltage. Conversely, a negative swing of

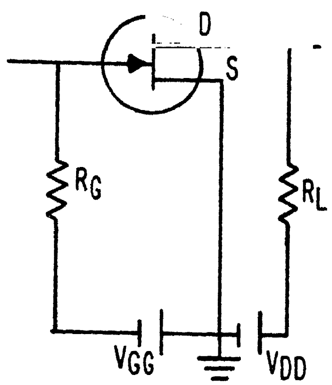
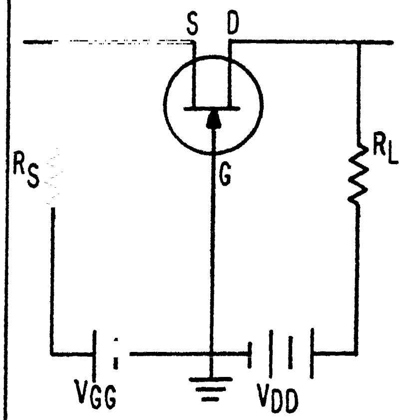
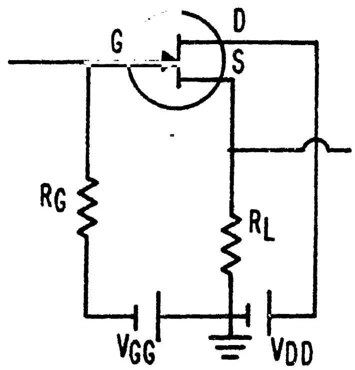
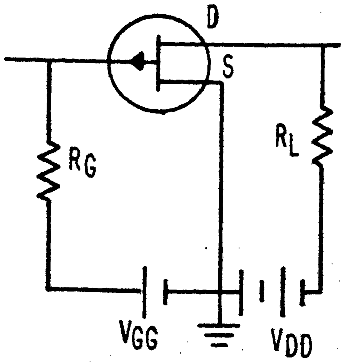
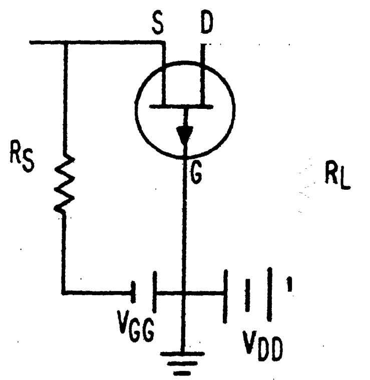
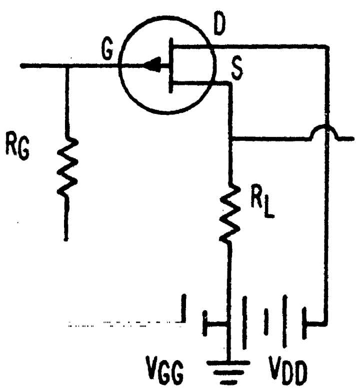
N-CHANNEL			
CHARACTERICS	High voltage gain High input impedance Moderate output imped. Input and output 180° out of phase	Moderate voltage gain Low input impedance Moderate output imped. Input and output in phase	No voltage gain Very high input imped. Low output impedance Input and output in phase
P CHANNEL			

Figure 8 Basic JFFT Cirsuits

4. Input and output voltages are in phase. Using the N-channel FET as an example, a swing of the source voltage in the positive direction (same as a negative swing of the gate voltage) decreases the drain current and increases the drain voltage. Conversely, a negative swing of the source voltage increases the drain current and decreases the drain voltage.

5. The common-drain's (source follower) input impedance is very high, and the output impedance is low. The output impedance of the common drain can be compared with the input impedance of the common-gate. A current gain is possible but there is no voltage gain.

6. nput and output voltages are in-phase. For example, using the N-channel JFET, a positive swing of gate voltage increases the source-to-drain current. This increase causes the source (output) voltage to swing in the positive direction. Conversely, a negative swing of the gate voltage decreases the drain current and the source voltage.

F. Symbols

1. Standardization of alphabetical and graphical symbols in electronics continues to be a problem for individuals, industries, and engineering societies. The advent of solid-state devices has resulted in some standardization, and certain procedures have become widely accepted. It should be stressed that, although it is now common to use the letter V for voltage in solid-state symbology, the letter E continues to be used in relation to vacuum tubes.

2. When a current is specified, the first subscript indicates the element at which the current is measured. When a voltage is specified, the first subscript refers to the element at which the voltage is measured, while the second subscript indicates the reference element. When no second subscript is used, the voltage measurement uses the common (ground) as a reference. The conventions of figure 9 are widely observed at the present time.

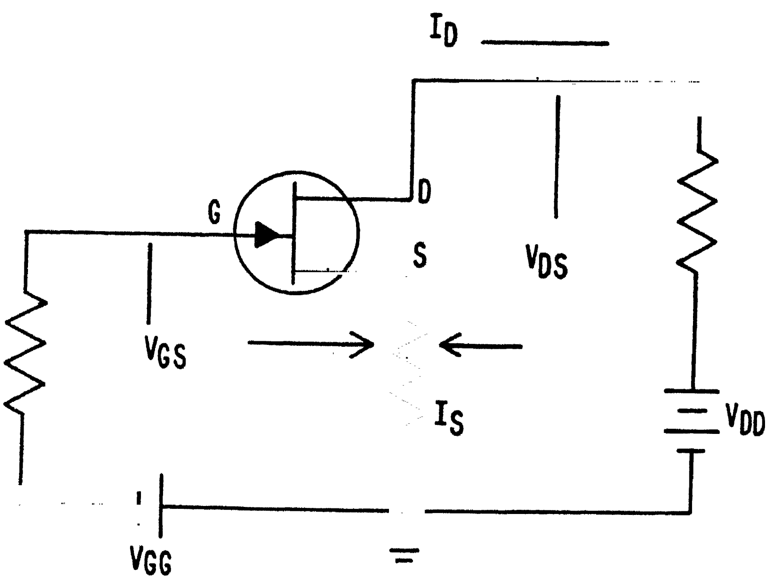


Figure 9 Key d-c Voltages and Currents of a JFET Circuit

?arameters and Specifications

.. The family of drain characteristics for a typical P-channel FET (2N2608) is given in figure 10. Note that the drain voltage used is negative. The less positive V_{GS}, the greater the magnitude of drain current (I_D). For example, a drain voltage of -10 volts and V_{GS} of +0.8 volts, I_D is 0.6 milliamperes. If the gate bias is reduced to +0.2 volts, I_D rises to about 1.4 milliamperes. The breakdown voltage is also indicated on the output characteristic curves. This is the point at which avalanche occurs on the V_{GS} = 0 curve.

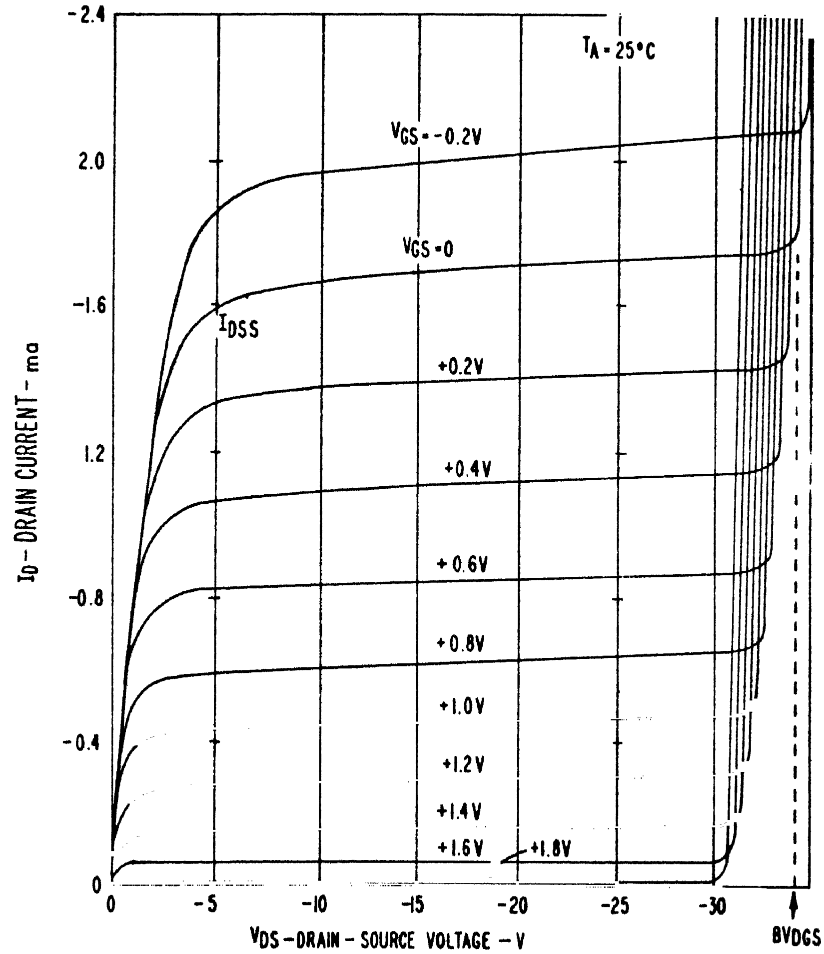


Figure 10 Typical JFET Output Characteristics for the 2N2608

3. An important parameter of a FET is the zero-gate-voltage drain current (I_{DSS}). The first two subscripts indicate that the drain-to-source circuit is of concern.

The third letter refers to the condition of the third element of the JFET relative to the reference element. In this case, the S indicates that the gate is shorted to the source (figure 11(A)). Usually I_{DSS} is specified for a definite V_{DS}. In the curves of figure 10, I_{DSS} is indicated for -5 volts.

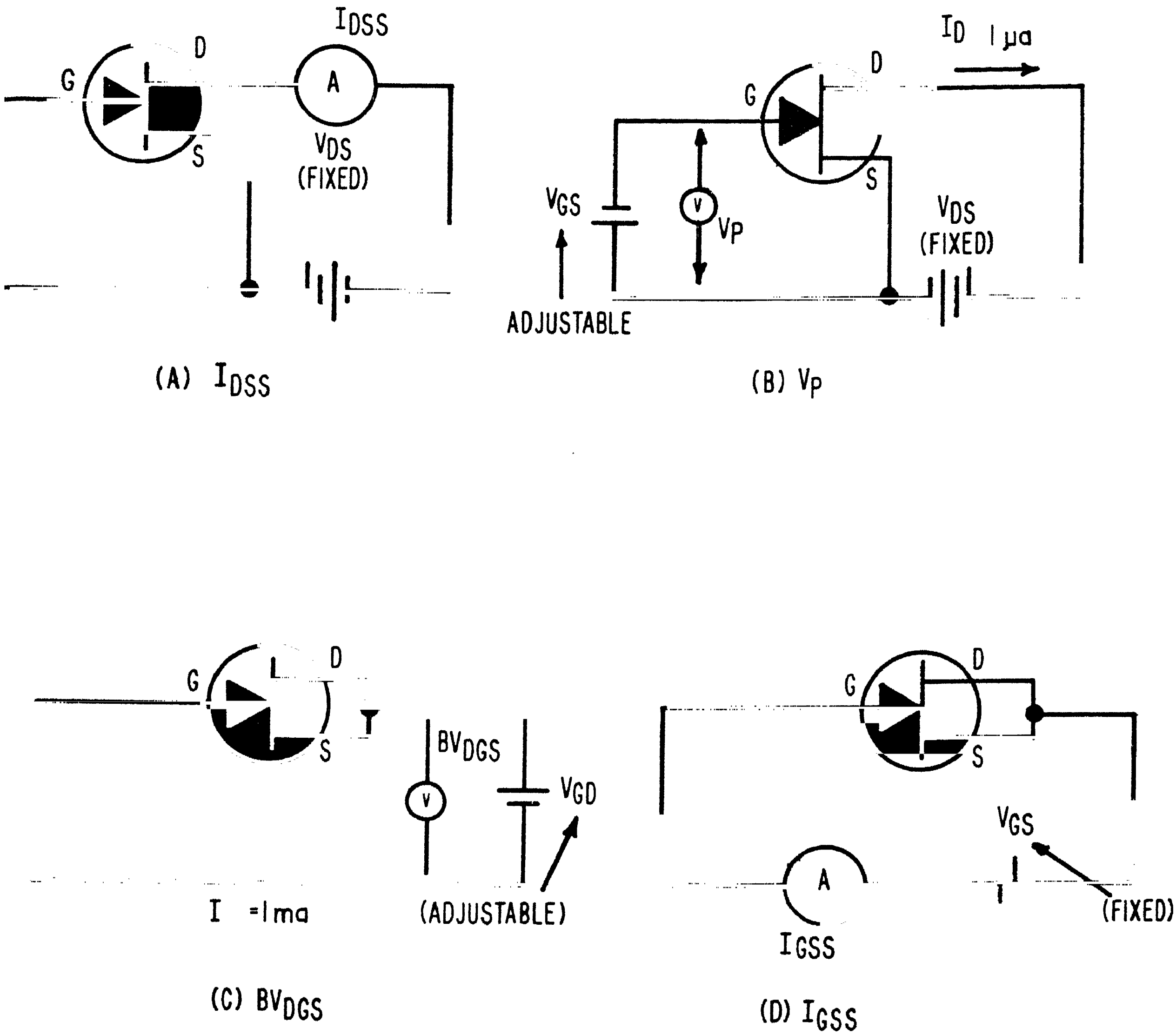


Figure 11 Measuring Key Fet Parameters

4. The gate-bias voltage (V_{GS}) at which the drain current will be reduced to practically zero for a specified drain voltage (V_{DS}) is known as the gate-source pinch-off voltage (V_P). Some insignificant value of drain current usually is specified as a practical cut-off value, such as 1 microampere or 0.1 percent of I_{DSS}. The method of measurement is given in figure 11(B). In the family of curves of figure 10, V_P is 1.8 volts for V_{DS} = 5 volts.

Table 1 - 2N2608 Specifications

Gate-Drain and Gate-Source Maximum Voltages	-30 volts
Gate Current (Forward Bias)	50 mA
Total Device Dissipation	200 mW
Storage Temperature Range	-65° to +200° C

	Parameter	Units	Min	Typical	Max
I_{GSS}	Gate-Source Cutoff Current at: V_{GS} = 30V, V_{DS} = 0	mA			10
I_{GSS}	Gate-Source Cutoff Current at: V_{GS} = 5V, V_{DS} = 0, T_A = 150°C	μA			10
BV_{GDS}	Gate-Drain Breakdown Voltage at: I_G = 1μA, V_{DS} = 0	Volts	30		
I_{DSS}	Drain Current at Zero Gate Voltage: V_{DS} = -5V, V_{GS} = 0	mA	0.90	1.60	4.50
V_P	Gate-Source Pinch-off Voltage at: V_{DS} = -5V, I_D = 1 μA	volts	1	2	4
g_{fs}	Small-Signal Common Source Forward Transconductance at: V_{DS} = -5V, V_{GS} = 0, f = 1kHz	μmho	1000	1600	
C_{gss}	Gate-Source Capacitance at: V_{DS} = -5V, V_{GS} = 1V, f = 140 kHz	pF	12	17	
NF	Noise Figure at V_{DS} = -5V, V_{GS} = 0, f_o = 1M, R_{gen} = 1M	dB		0.5	3

5. Certain other parameters are important, breakdown voltage B_{VDGS} as I_{GSS} is temperature dependent and is one of the major disadvantages of the junction JFET.

6. There are certain maximum ratings which, if exceeded, would result in the destruction of the transistor. A summary of the key parameters and specifications for 2N2608 as furnished by the manufacturer are shown in Table 1.

Determining a Load Line

1. A load line can be drawn (figure 12) on the FET's characteristic curves.

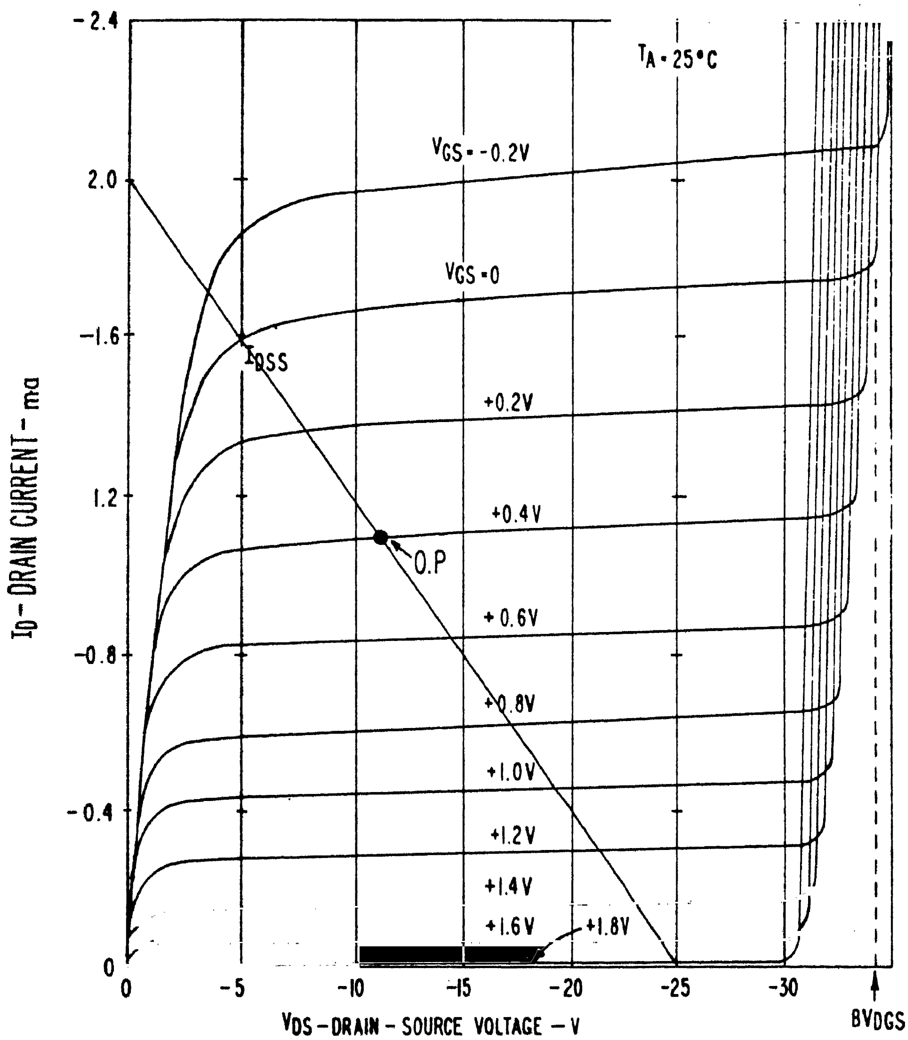


Figure 12

The load line represents a resistance of 12.5 kohms. The supply voltage (V_{DD}) is 25 volts. With an input signal at 0.4 volts peak-to-peak at the operating point, the output voltage will be 6.5 volts peak-to-peak.

The voltage gain is: $A_V = \frac{\Delta V_{DS}}{\Delta V_{GS}} = \frac{6.5}{.4} = 16.25$

2. At the operating point, the transconductance (g_{fs}) is about 1375 μmhos. Using the formula

   $A_V \approx g_{fs} R_L$: $A_V \approx (1375 \times 10^{-6})(12.5 \times 10^3) \approx 17.2.$

   The slight discrepancy in this case is because of the error in reading the curves; however, the approximation is as accurate as most electronic components.

I. Noise Considerations

The noise content of a FET is low in comparison to a vacuum tube or a bipolar transistor. The three sources of noise in a field-effect transistor are: The gate-leakage-current shot noise, thermal or resistance noise that results from the agitation of the charge carriers in the channel, and low-frequency noise (1/f noise).

J. Frequency Response

1. Low power junction FETs have a gate-to-drain capacitance (C_{gd}) ranging from 1 to 100 pF. This capacitance increases as the drain-to-source voltage is reduced and approaches the pinch-off voltage. As a result of this capacitance (C_{gd}) the "Miller effect" occurs in junction FET's.

2. A regular (bipolar) transistor's low impedance base input tends to shunt a large portion of the transistor's high impedance internal feedback to the emitter. The Miller effect in regular transistors is, therefore, not as great as in FETs where the input signal at the gate, like the internal feedback signal, is usually also of high impedance.

3. The Miller effect in FETs can be reduced by increasing the drain to source voltage, reducing the circuit's input impedance or with a feedback circuit opposing the semiconductor's internal feedback.

4. Theoretically, junction FETs should be able to handle frequencies up to 1 GHz, although the maximum usable frequency is below this value. The figure of merit is also known as the cutoff frequency because it is at

this point the power gain of the device falls off to 1. Stated as an equation:

$$f_{co} = \frac{g_{fs}}{C_{GD}}$$

FETs can be made to operate well as common-source amplifiers at frequencies of several hundred megahertz.

Temperature Effects

1. Junction FETs, like regular transistors, are normally affected by changes in temperature (T_A). Measurements indicate that their pinch-off voltage (V_P) usually increse at about 0.2% per 8°C.

2. Although FET PN junctons are affected by temperatures, the gate current stability of silicon FETs approaches the base current stability of bipolar silicon transistors. Provided the circuit's gate-to-source resistance (R_G) lies between 1 and 10 megohms.

3. Two opposing effects of temperature change in JFETs result in a linear decrease in I_{DSS} with increasing temperature, causing the current to decrease about 0.6% per °C. This drift can be reduced by operating the FET a low level of I_D.

4. The use of JFETs with lower pinch-off voltages also reduces I_D drift. Measurements show that FET's having a 0.63V pinch-off experience no temperature drift when operating at their normal I_{DSS} and g_{fs}.

JFET Standardization--In a previous lesson, it was shown that few transistors of the same type have exactly the same characteristics. The same problem exists with JFETs. Many FETs of the same type have I_{DSS} and g_{fs} ratings that vary by as much as 2 to 1.

Advantages and Disadvantages:

1. It should be apparent that the primary advantages of JFETs are:

   a. Very high input impedance.

   b. Low noise characteristics.

   Although their voltage gains are relatively low, once a low impedance point occurs in a circuit, the bipolar transistor could be used to get the required gain using cascaded stages.

2. The disadvantages associated with JFETs are:

   a. JFETs are temperature sensitive.

   b. Low gain as compared to bipolar transistors.

   The reader must be aware that, although the JFETs characteristics are temperature sensitive, they are not near as sensitive to T_A variations as the bipolar transistor.

II. AVALANCHE DEVICES

A. Avalanche is defined as a cumulative process by which charged particles collide with and ionize the medium through which they are traveling.

B. As long as the current-handling capacity of the device is not exceeded during the avalanche process, some very useful characteristics can be utilized.

   1. Zener Diode

   A zener diode is a PN-junction diode that is more heavily doped than the average diode. It is designed to operate in the reverse bias breakdown, or avalanche region without damaging the junction. Since the zener diode operates in the reverse-bias direction or region, it operates on minority carriers.

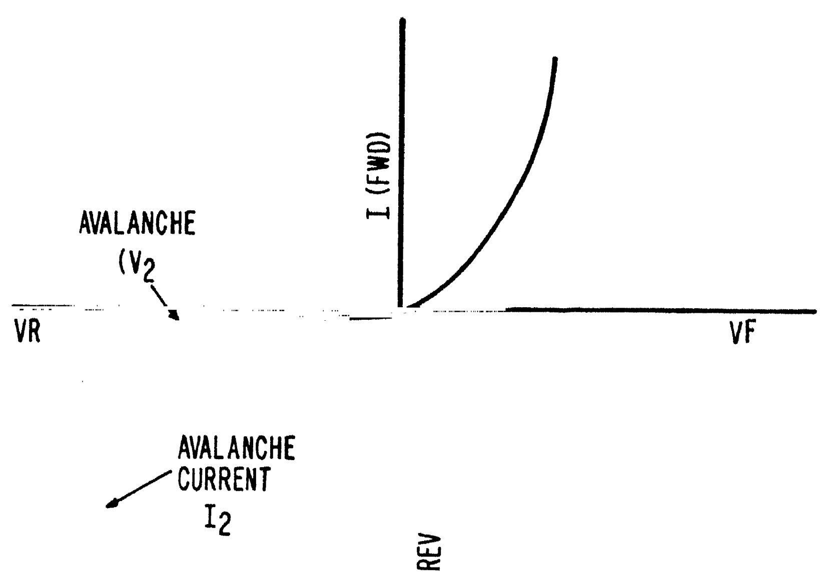


Figure 13

As shown in figure 13, if a zener diode is biased in forward direction, VF, it has characteristics similar to an ordinary junction diode. With reverse-bias applied, VR, the zener diode will operate as a voltage reference device. The voltage at which the diode breakdown (VZ) occurs is determined by the type of semiconductor material used, the type of doping material used, and the actual doping level of the zener diode.

Once the diode goes into the avalanche region, the voltage across the diode will remain almost constant. The reverse-bias potential accelerates the minority carriers to such a velocity that they physically dislodge other carriers from the crystal lattice. The result is a very large current flowing in the zener diode. If the voltage applied to the junction decreases, the acceleration of the carriers will decrease, which results in less current through the diode. With less current flow, the zener impedance increases and the voltage across the diode remains constant.

The constant voltage characteristics of the zener diode (in the avalanche region) are particularly useful in voltage regulator circuits.

Figure 14 is a basic voltage regulator circuit employing a zener diode as the regulating component.

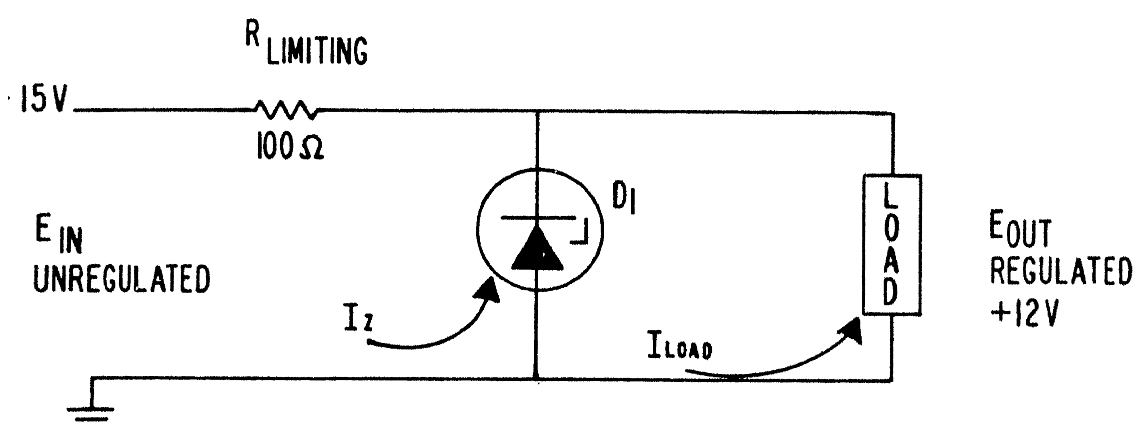


Figure 14

The zener diode, D_1 will regulate the output voltage at VZ (12 volts). The static load current is 10 mA and the zener current, IZ, is 20 mA; therefore, in the static condition, 30 mA of current will flow through $R_{limiting}$ dropping 3 volts.

a. If the load current increases, the voltage dropped across $R_{limiting}$ will increase. This increased voltage drop will cause less voltage to be supplied to the zener diode decreasing IZ. Thus, the current flow through $R_{limiting}$ decreases and the output returns to +12 volts.

b. If the unregulated voltage increases, the voltage suppied to the zener diode will increase. This increased voltage (VZ) will cause an increase in IZ. When IZ increases, the voltage drop across $R_{limiting}$ will increase, thus returning the regulated output to +12 volts.

2. Four-layer didoes (PNPN)

a. A PNPN diode is a 4-layer, 3-junction device that operates in the avalanche mode.

b. As shown in figure 15, the layers are alternately doped P- and N-type semiconductor materials with ohmic contacts to the P-type and N-type regions. The ohmic contact to the P-type region is called the anode, and the contact to the N-type region is called the cathode. Notice that the internal P- and N-regions are floating.

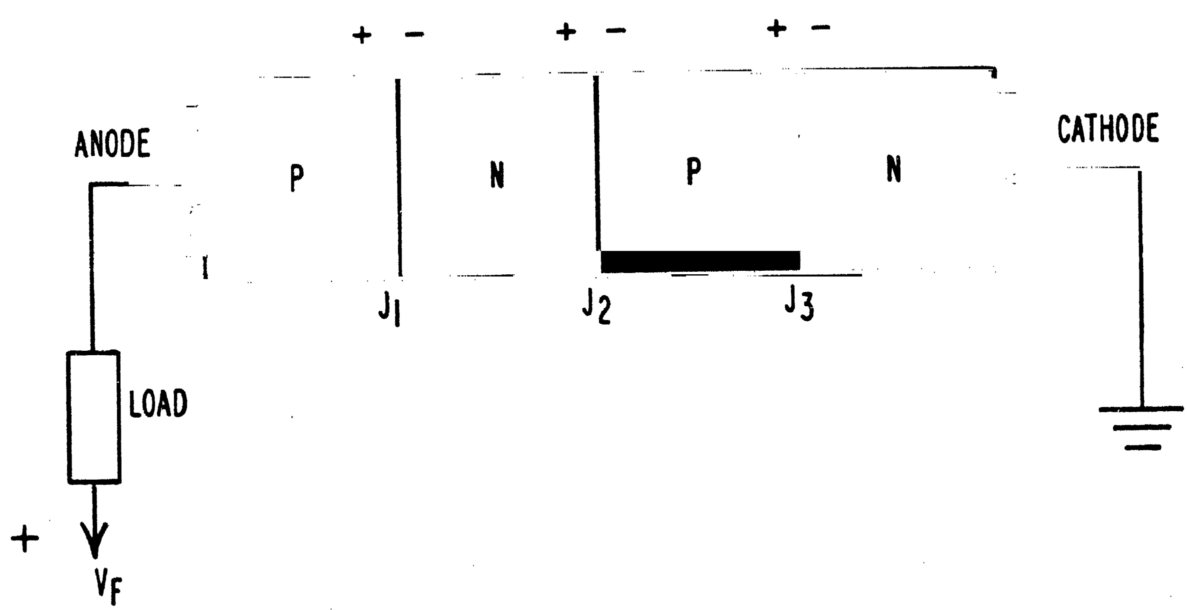


Figure 15

c. With applied voltage, positive to anode and negative to cathode, the voltage gradients across the device are as shown in figure 15. J1 and J3 are forward-biased and J2 reverse-biased. With J1 and J3 offering a very small resistance (forward-biased), most of the voltage across the device is dropped across the reverse-biased junction J2 and forward current IF, is very small. The device is said to be "OFF" or blocking, which represents a high resistance between anode and cathode.

d. With J2 reverse-biased, only minority carriers flow through the internal P- and N-areas. The negative voltage on the N-type cathode injects electrons into the internal P-type area where they flow as minority carriers, and the positive voltage on the P-type anode injects carriers into the internal N- type area where they also flow as minority carriers.

e. As can be seen in figure 15, as the applied voltage (V_F) is increased, more injected holes from the P-type anode will diffuse through the internal N-type material and be controlled by the internal P-type material. The internal P-type material becomes more positively charged (contains more holes), thus increasing the forward-bias on J3.

f. At the same time J3 is increasing its forward-bias, the N-type cathode is injecting more carriers into the internal P-type material which diffuse into the internal N-type region which becomes more negatively charged (more electrons) increasing forward-bias at J1.

g. As J1 and J3 increases their forward bias, their junction resistance decreases and more of the applied voltage (V_F) is felt at the reverse-bias junction J2, increasing the depletion region at J2.

h. As the depletion region at J2 increases, the effective N and P areas are reduced.

i. Figure 16 depicts the condition now existing; i.e., the increased depletion region at J2 and the reduced efective areas of the internal N and P-type materials. As the external voltage (V_F) continues to increase, the carriers crossing the depletion region gain velocity as they are swept across the junction. When the velocity the carriers gain while crossing the junction is great enough, free carriers are produced in the internal N- and P-type materials by the high velocity carriers striking valence electrons.

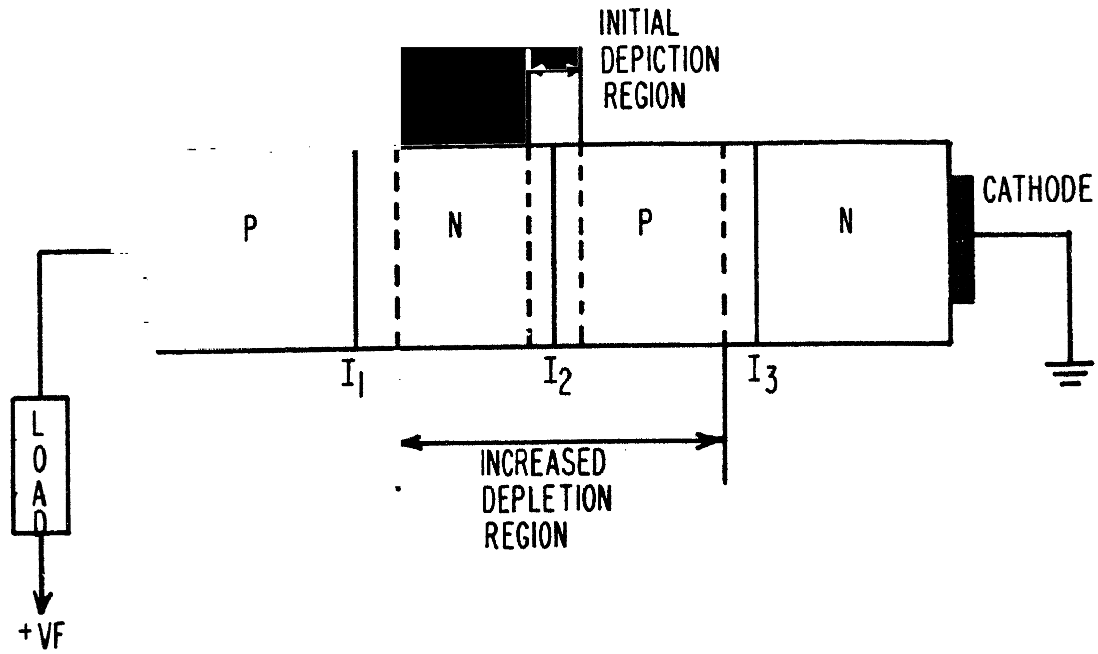
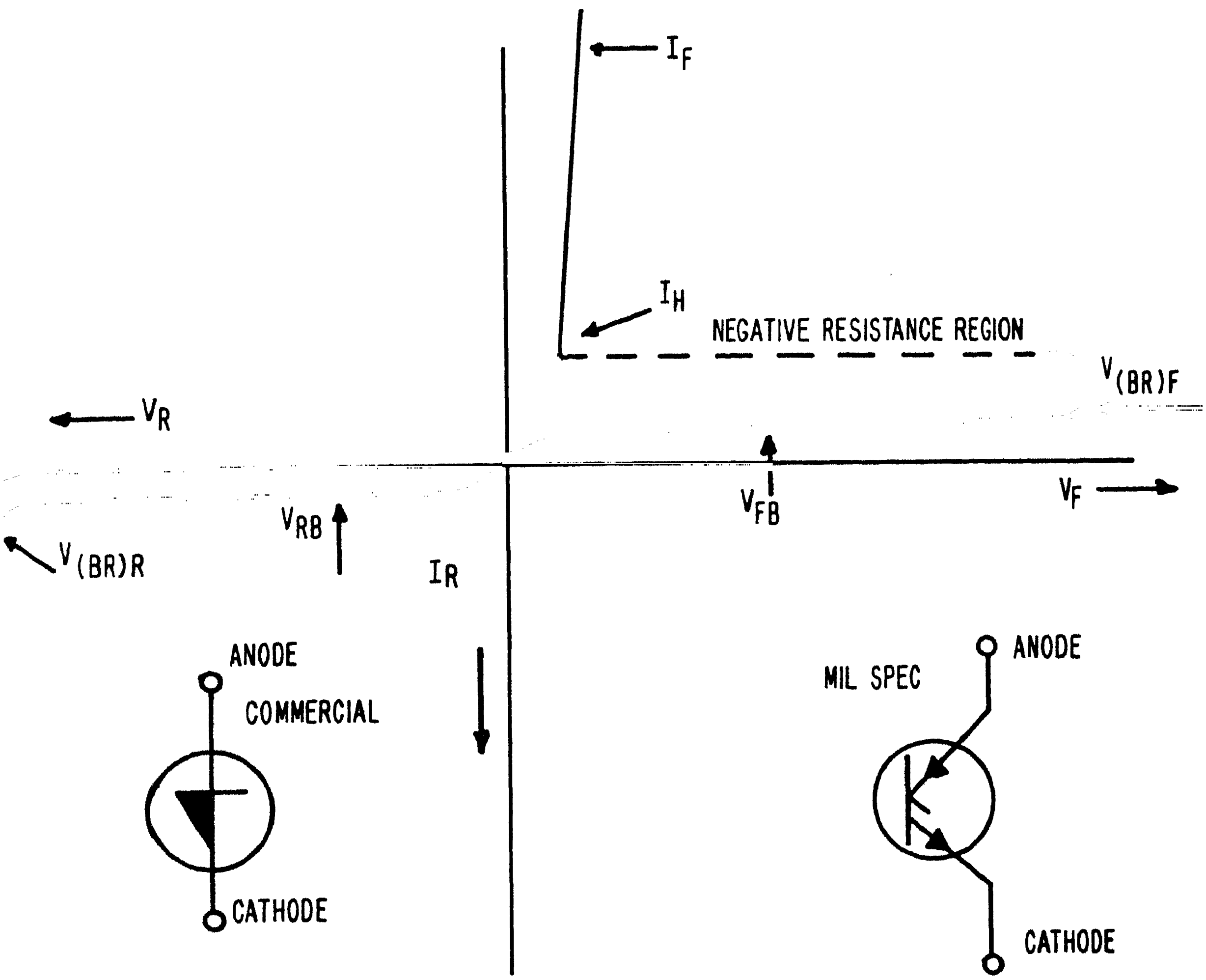


Figure 16

j. This process is accumulative and anode current starts increasing rapidly because of the many free carriers generated. Avalanche soon occurs and the current must be limited by external series resistance or else the device will destroy itself. The device is said to be switched "ON" and represents a low resistance between anode and cathode.

k. The PNPN device thus acts as a switch. (1) OFF, or high resistance, very low current flow. (2) ON, or low resistance, heavy current flow. When the device is turned on, a specific amount of current (I_F) must be maintained to keep it on. This current is specified as holding current, I_H. Another current rating that must be considered is latching current I_L. The latching current rating specifies a value of anode current, slightly higher than the holding current, which is the minimum amount required to sustain conduction immediately after the device is switched ON. In other words, the PNPN switch must be driven deep into avalanche initially to sustain normal operation.

l. A graphical analysis of the PNPN device as shown in figure 17 will show the negative resistance region inherent to PNPN devices.



PNPN CHARACTERISTIC GRAPH

Figure 17

m. The applied voltage V_F, anode positive to cathode, that results in a small current flow is called the forward blocking voltage, V_{FB}. As the forward voltage is increased, a sudden increase in current is apparent as the device switches "ON." The minimum voltage necessary to turn the device on is called the "forward breakover voltage," $V_{(BR)F}$. When the device is "ON," I_F increases and V_D decreases, resulting in a negative resistance region. The device may be turned OFF several ways.

(1) Increasing the external series resistance.

(2) Decreasing the applied voltage to zero.

(3) Communication--which will be covered in detail shortly.

n. Notice that the device will exhibit normal diode characteristics under reverse bias conditions; i.e., as reverse-bias, V_R, is increased avalanche will occur at the reverse breakdown point labeled $V_{(BR)R}$. The PNPN switch can be destroyed in the reverse-bias avalanche region and should not be operated with reverse-bias between anode and cathode.

o. PNPN switches are used for trigger devices and for low-cost sweep generators and timers.

p. Figure 18 is another sweep-generator circuit using a PNPN switch.

Figure 18

When V_P is applied to the anode of the PNPN diode, the capacitor starts charging toward V_F. As the voltage across the capacitor reaches $V_{(BR)F}$, the diode turns ON and discharges the capacitor. A sawtooth waveform is thus produced across the diode. R_{lim} limits the current to a safe value and with C1 determines the rate of firing.

3. Silicon Controlled Rectifiers (SCR)

a. Basically, the SCR is a PNPN structure with another ohmic contact made to the internal P-type region.

b. Figure 19 represents the basic SCR including the additional ohmic contact.

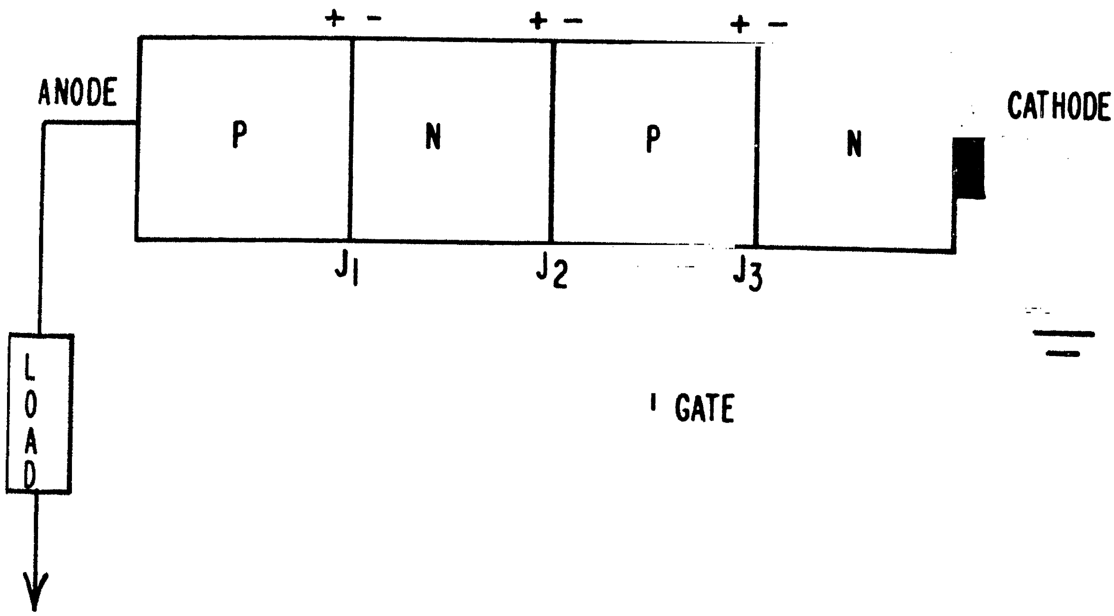


Figure 19

The additional lead is called the gate and aids in the "turn-on process."

c. The SCR is normally operated with $V_F << V_{(BR)F}$, where $V_{(BR)F}$ represents the forward breakover voltage, as was the case with the basic PNPN device. With the gate open, the SCR will be "OFF" or in the blocked condition. When a positive voltage is applied to the gate, current will flow into the gate (I_{GT}).

d. The current flow (electrons) in the gate is injected from the N-type cathode; however, many injected carriers will diffuse through the internal P-type material to the internal N-type material. The internal N-type material now takes on a negative charge (excess electrons) increasing the forward bias on J1. The increased forward-bias on J1 increases injected holes through J2 from the anode.

e. As more holes flow across J2 from the anode, more electrons must flow across J2 from the cathode, thus increasing the forward-bias on J1 even more. This process is accumulative and the device quickly switches "ON." Thus, I_{GT} aids in turning the SCR ON.

f. Figure 20 is a graphical analysis of the turn "ON" process just described and also includes the commercial and Mil-Spec symbols for the SCR.

g. Notice that as I_{gate} is increased, turn "ON" (breakover) occurs at lower values of V_F. This is quite an advantage over the basic PNPN switch where there was no control over the breakover point.

h. Also apparent in figure 20 is the fact that the SCR acts as a bistable switch; i.e., "ON" or "OFF" when V_F is a positive voltage and V_{gate} is also positive.

i. The SCR is the solid state equivalent of the gaseous thyratron tube which is switched "ON" by a voltage pulse on its control grid which ionizes the tube. The SCR on the other hand receives a current pulse on its gate which aids in the "avalanche" process in much the same manner as a tube ionizes. Like the thyratron's grid, the SCR's gate loses all control once the device turns on. The SCR must be turned off in the same manner that the PNPN device was.

(1) Reducing the anode-cathode to zero.

(2) Driving $I_F < I_H$.

(3) Forcing commutation.

j. The main advantage of the SCR is its ability to control heavy load currents with light control (gate) currents. Currently SCR's have wide applications among them, being; motor speed conrols, heating controls, and ignition systems.

k. As stated earlier, the SCR may be turned off by several methods:

(1) Reducing anode current to zero.

ing I_F to $< I_H$.

on.

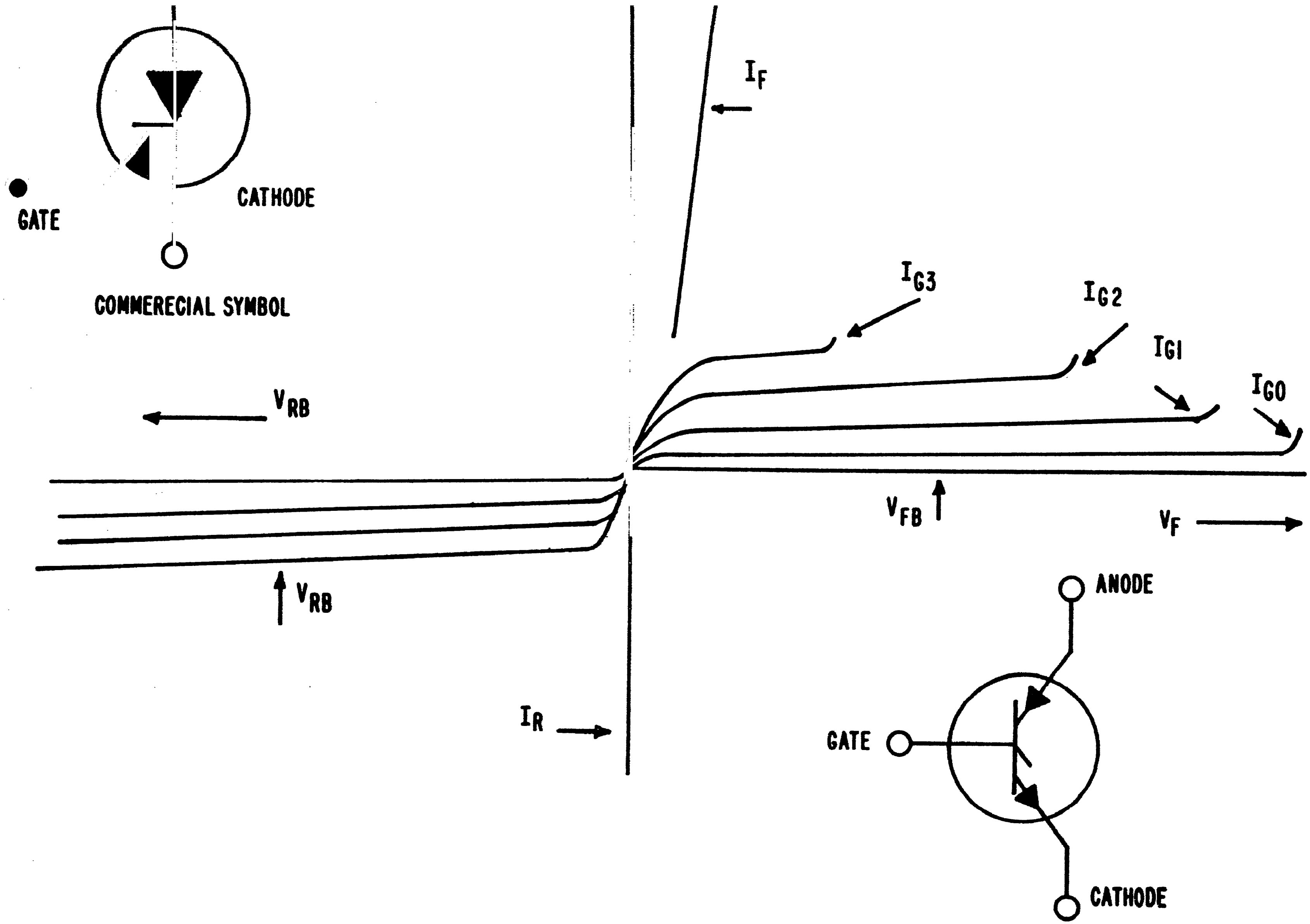

GATE
CATHODE
COMMERECIAL SYMBOL
I_F
I_{G3}
I_{G2}
I_{G1}
I_{G0}
V_{RB}
V_{RB}
V_{FB}
V_F
I_R
ANODE
GATE
CATHODE

Figure 20

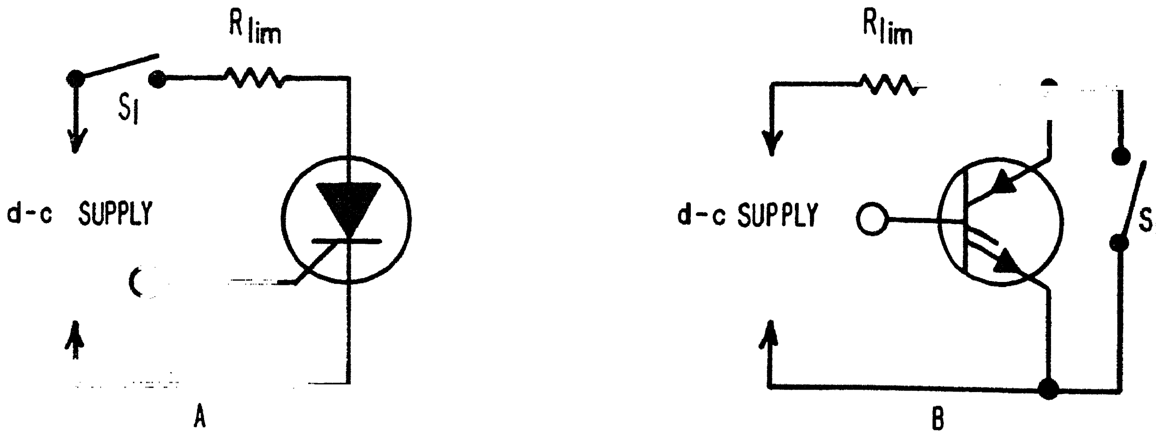


Figure 21

Figures 21a and 21b will definitely "fit the bill" for conditions (1) and (2) above; however, it would be difficult to operate the switch at a very high frequency or with any appreciable current. Commutation is the most often used "turn off" technique employed. This method switches current from some energy source to force current through the SCR in the reverse direction. There are six distinct classes of commutation.

(1) Class A - Self-commutated by resonating the load.

(2) Class B - Self-commutated by an LC circuit.

(3) Class C - C or LC switched by another load-carrying SCR.

(4) Class D - C or LC switched by an auxiliary SCR.

(5) Class E - An external pulse sound for commutation.

(6) Class F - A-c line commutation.

l. As class F, a-c line commutation is the most common turn-off technique used; it will be the method analyzed. Figure 22 will be used in the analysis.

m. Assuming that the gate is triggered at the beginning of the a-c cycle, the SCR will conduct for 180°. As the a-c waveform on the anode goes negative, the SCR will be "cut-off" as it requires a positive anode voltage, V_F. Thus, a-c power

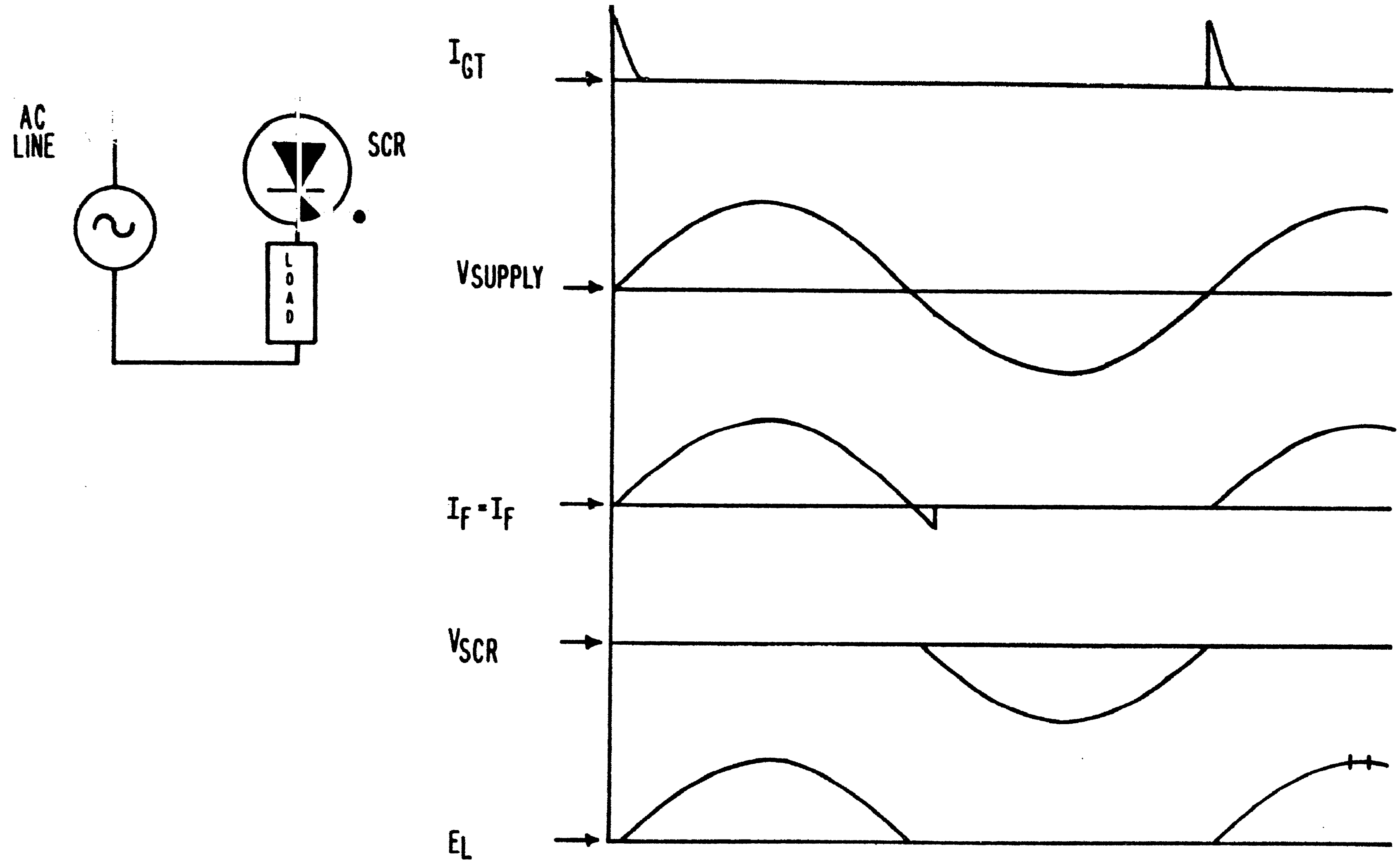


Figure 22

would be delivered to the load during 180° of the line voltage. By controlling the phase of the gate pulse with respect to the a-c line voltage, the power to the load can be varied from zero to maximum when the gate pulse is present at the 000° point of the a-c line voltage.

III. UNIJUNCTION TRANSISTORS

A. The unijunction transistor (UJT) is basically a silicon bar with two contacts and a PN junction.

B. Figure 23 shows the construction of an UJT and its Mil-Spec symbol.

1. The two ohmic contacts made to the base (silicon bar) are called B_1 and B_2 (N-type material). B_1 is the low potential or common side and B_2 is the high potential or voltage supply side. B_2 will be biased positive in respect to B_1 (V_{B2B1}).

2. The PN junction formed is the emitter which will be positive in respect to B_1.

a. R_{BB} is the interbase resistance between B_1 and B_2 with typical values ranging from 4 kΩ to 10 kΩ.

b. Figure 23A depicts the condition existing at the emitter base junction with a voltage applied to the B_2B_1 leads (V_{B2B1}) and the emitter voltage, V_E, equal to zero.

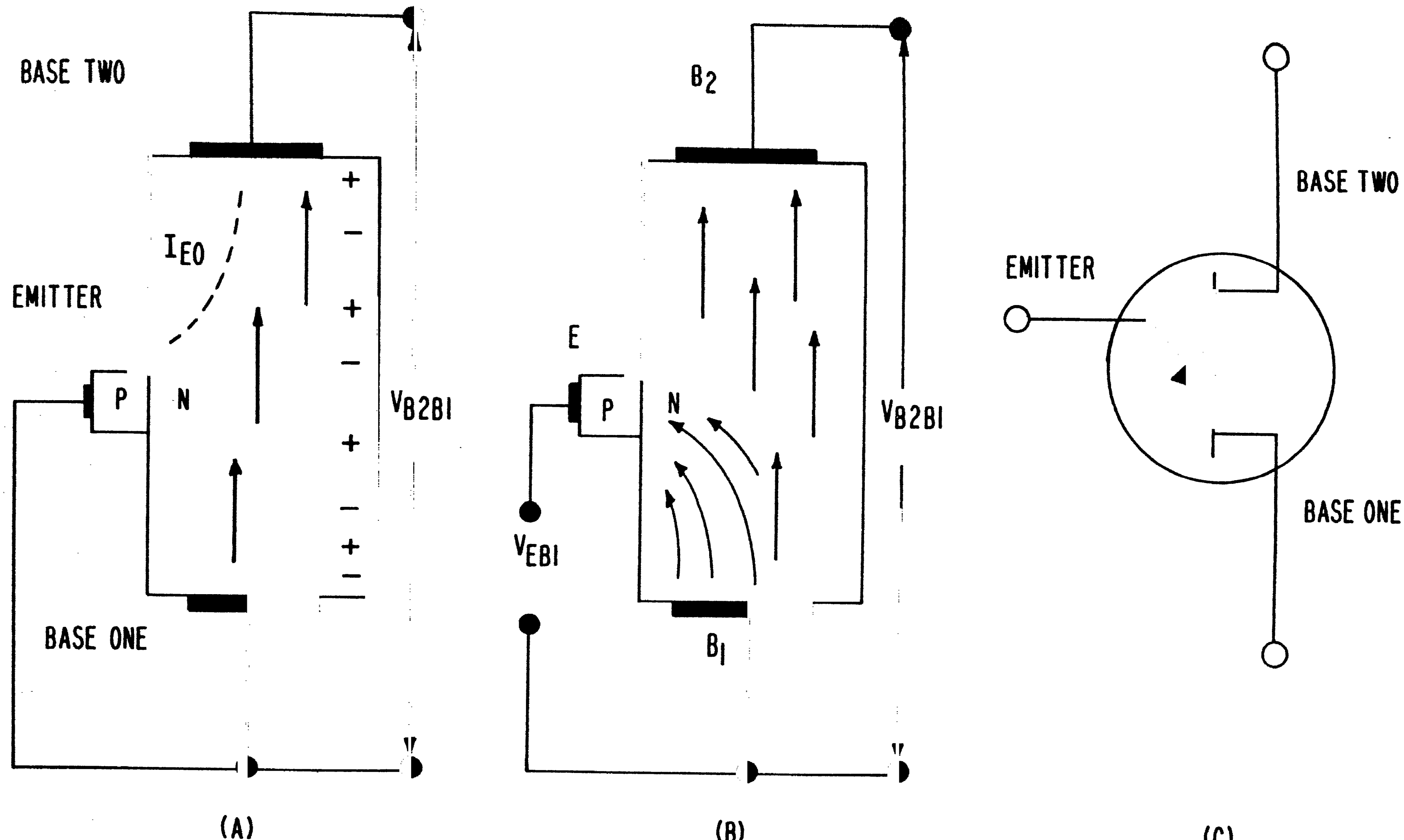
c. With V_{B2B1} applied, R_{BB} develops voltage gradients throughout the N-type silicon bar. The voltage opposite the PN junction, between B_2 and B_1, is of some positive value.

d. Under these conditions, the PN junction is reverse-biased and only a small amount of leakage current (I_{EO}) will flow in the emitter lead. The current flow in the device will be essentially between B_2 and B_1.

e. As shown in figure 23B, as the emitter voltage, V_E, is increased, positive in respect to B_1; i.e., V_{EB1}, the PN junction will become forward-biased.

(1) The emitter injects holes into the N-type bar where they are swept toward B_1.

(2) Electrons from B_1 combine with the injected holes increasing I_E (emitter current).



Unijunction Transistor
Figure 23

f. The resistance between the emitter and B_1 decreases because of this increased current flow. The UJT is now turned on.

3. The value of V_{EB1}, which forward-biases the emitter-bar junction, is called the peak point emitter voltage, V_P.

4. Thus, the unijunction transistor has many of the characteristics of a gas thyratron. Until the control voltage (V_{EB1}) reaches a certain value (V_P), the unit is reverse-biased and essentially cut off. The instant the critical value is exceeded, the emitter PN junction becomes forward-biased and emitter current increases considerably.

5. A simplified equivalent circuit for the unijunction transistor may be developed as shown in figure 24.

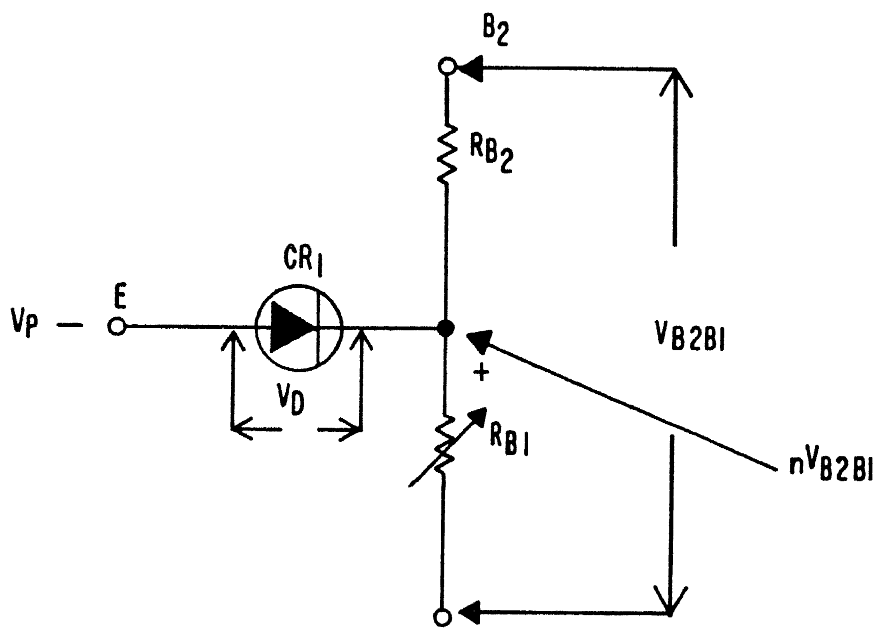


Figure 24

Diode CR_1 represents the emitter-bar PN junction, wit RB_1 representing the resistance of base 1 and R_{B2} representing the resistance of base 2. R_{B1} is shown as variable since it does vary as a function of the emitter-base 1 current. (As emitter current goes up at the firing point, the resistance R_{B1} decreases.)

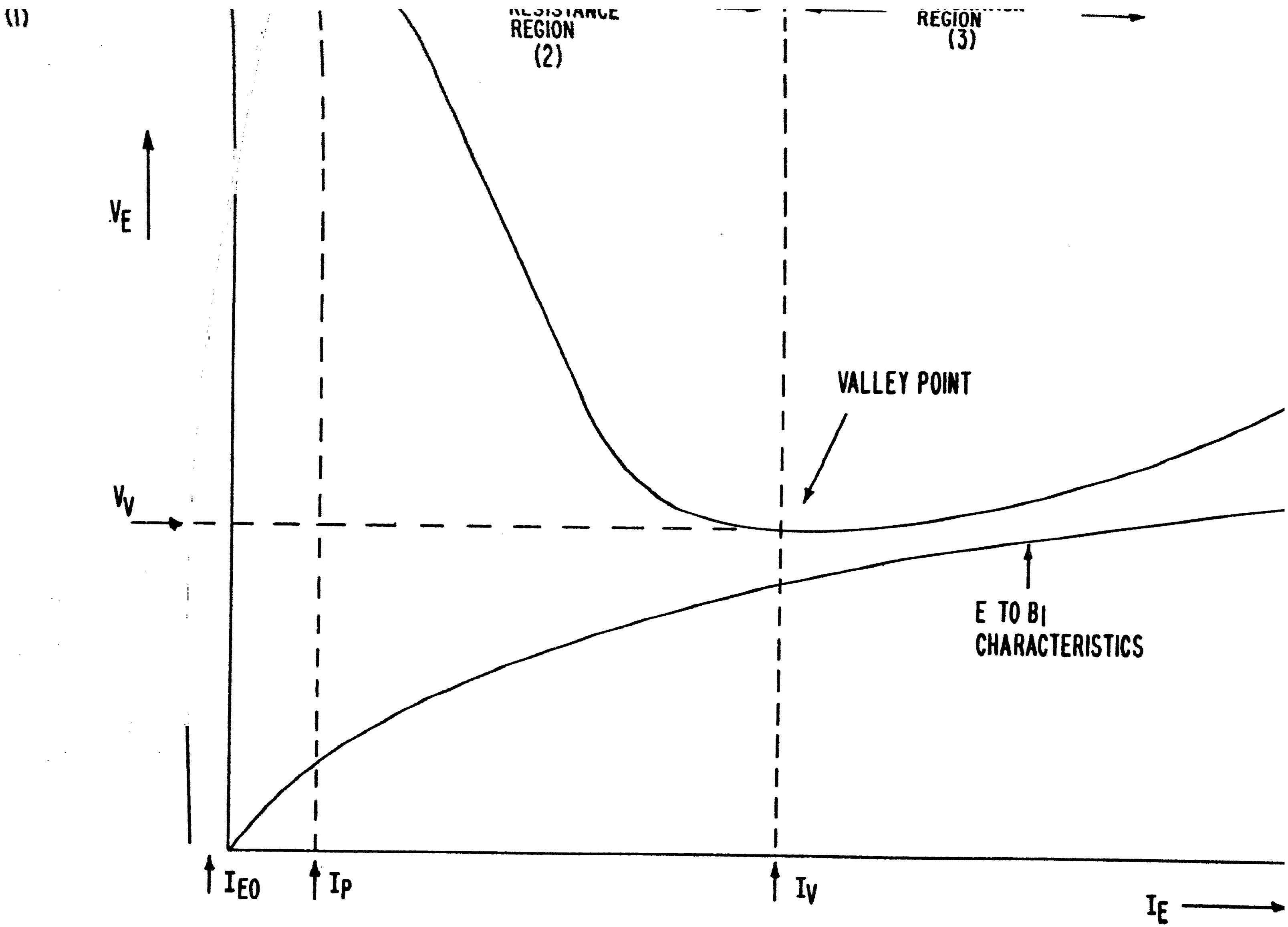


Figure 25 - UJT Characteristics

6. As previously stated, V_P is the minimum voltage necessary to forward bias the emitter-bar PN junction and turn it on. As can be seen in figure 24, the greater the magnitude of V_{B2B1}, the larger the voltage developed at the top of R_{B1} (ηV_{B2B1}). The parameter η is called the intrinsic standoff ratio and represents the percentage of the voltage V_{B2B1} developed across R_{B1}. The manufacturer of the UJT supplies this parameter in his specification sheet (typical values range from 0.51 to 0.82).

7. Also shown in figure 24 is a voltage drop across the diode CR_1 V_D. This voltage will be present in the static condition because of I_{EO}.

8. In order to turn the UJT on, the emitter voltage must be positive with respect to ηV_{B2B1}. Thus, $V_P = \eta V_{B2B1} + V_D$. For example:

   Given: V_{B2B1} = 10 volts
   2N2646 $\eta = .51$
   Characteristics V_D = .5 volts

   Find: The minimum voltage required to turn on the UJT (V_P).

   Solution:
   $$V_P = \eta V_{B2B1} + V_D$$
   $$V_P = (.51)(10V) + .5\ V$$
   $$V_P = 5.6 \text{ volts}$$

C. A typical characteristic curve of a unijunction transistor is shown in figure 25. This curve has three distinct regions. Region 1 is the cutoff region, where the emitter is reverse-biased. As the voltage applied between the emitter and B_1 rises, the current (I_E) rises too, although the total current seldom exceeds 10 µA (I_{EO}) Region 1 ends when the applied voltage reaches the point marked "V_P". At this point, the UJT "fires" with a large increase in current and a decrease in the voltage drop between emitter and B_1. This is the negative resistance region, and it is this feature which gives the UJT its unique properties, as we shall see presently. Eventually there is a point reached, called the minimum, or valley point, beyond which the device behaves as a positive resistor. That is, the current increases slowly with voltage. This region is called the saturation region. The UJT switches from the cutoff to the saturation region quite rapidly because of the highly unstable negative resistance region.

D. Figure 26 is a tyical circuit using a UJT in relaxation oscillatory mode.

   1. Initially, capacitor C_1 is not charged and the emitter potential is zero. However, because C_1 is connected

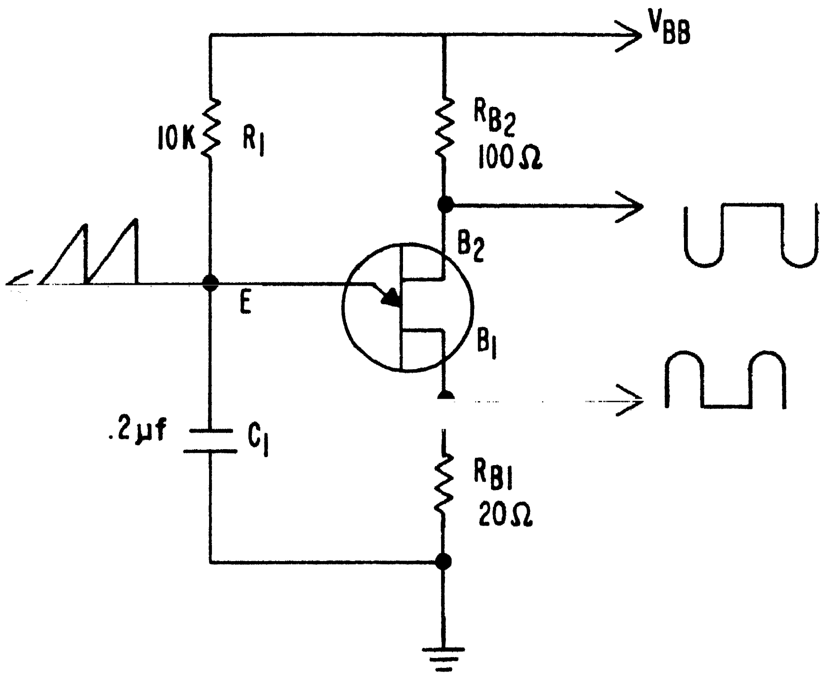


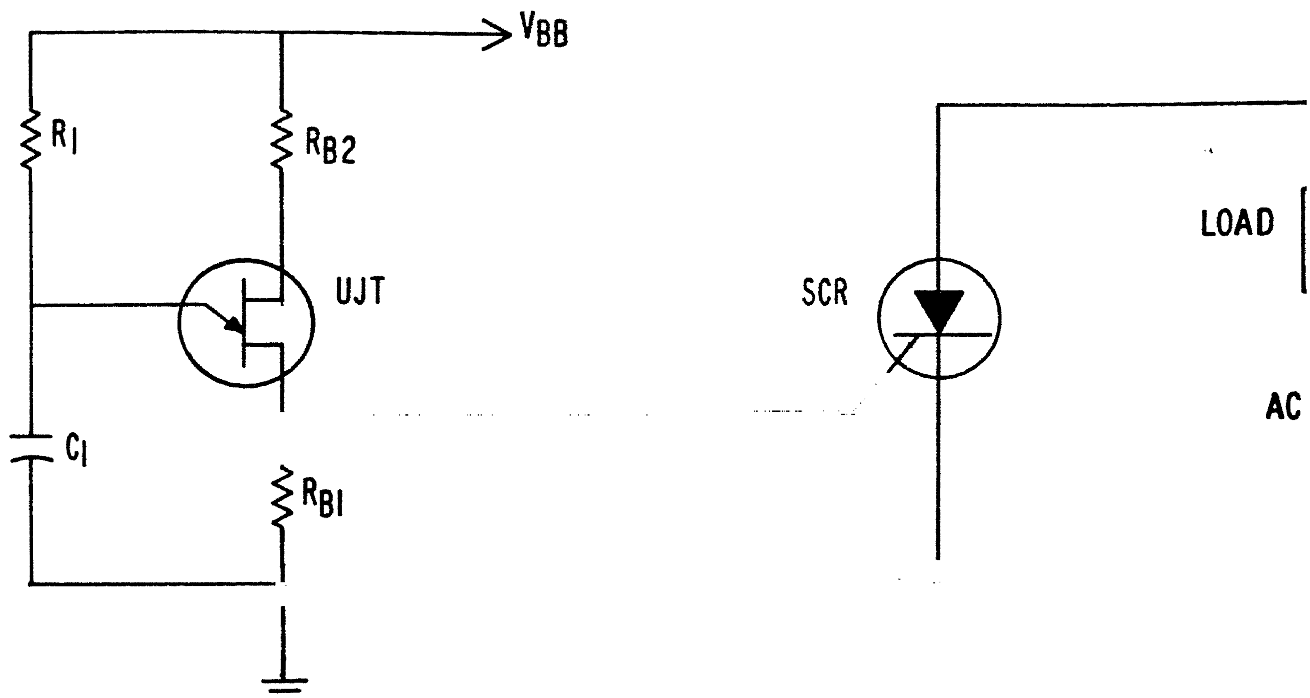
Figure 26

to the power supply (V_{BB}) through R_1, it will slowly charge until enough voltage develops across C_1 to forward-bias the emitter junction (V_p). At this point, the unijunction transistor "fires." C_1 now discharges rapidly through R_{B_1} and the low resistance of the emitter - B_1 junction. With C_1 discharged, the transistor returns to its nonconducting state, and the cycle repeats itself.

2. The waveform developed in this circuit are also shown in figure 26. The voltage across C_1 is a sawtooth wave, possessing a slow rise and a rapid descent. At the time of firing, the current through the entire silicon bar rises developing a positive pulse at the top of R_{B_2} and a negative pulse at the bottom of R_{B_1}. Note the extreme simplicity of this circuit, requiring only three resistors and a capacitor. As a matter of fact, if only a sawtooth waveform is desired, R_{B_1} and R_{B_2} can be dispensed with.

E. Figure 27 is another typical UJT trigger as used to control an SCR.

1. R_{B1} develops the positive trigger pulses necessary for the SCR.



UJT CONTROL OF AN SCR

Figure 27

2. R_{B2} is used to limit the current through the UJT to prevent excessive current which could destroy the device.

3. R_1 and C_1 time the trigger period and, in turn, the average value of I_{load}.

4. The UJT is probably the most versatile triggering device for the SCR because of its relative simplicity and low power consumption.

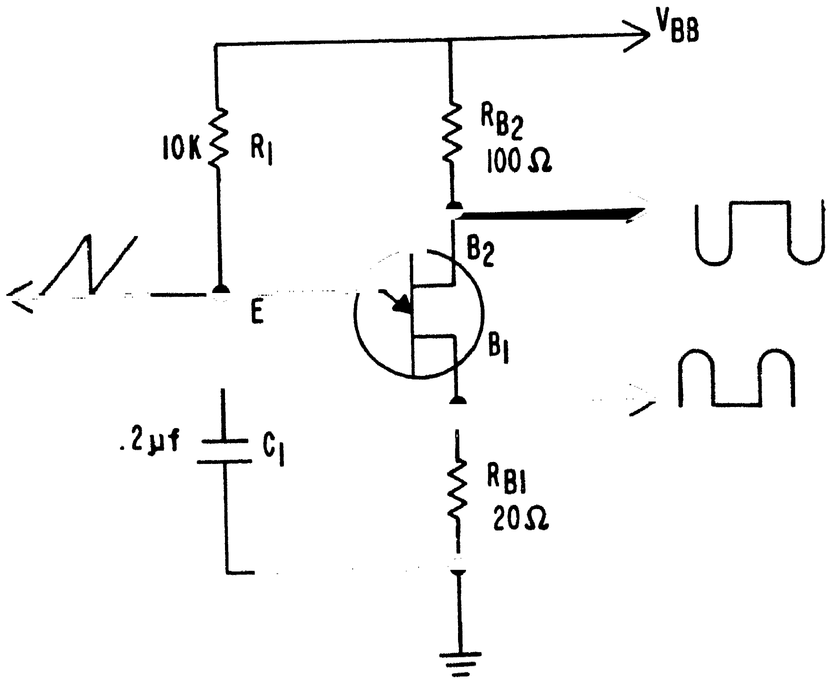


Figure 26

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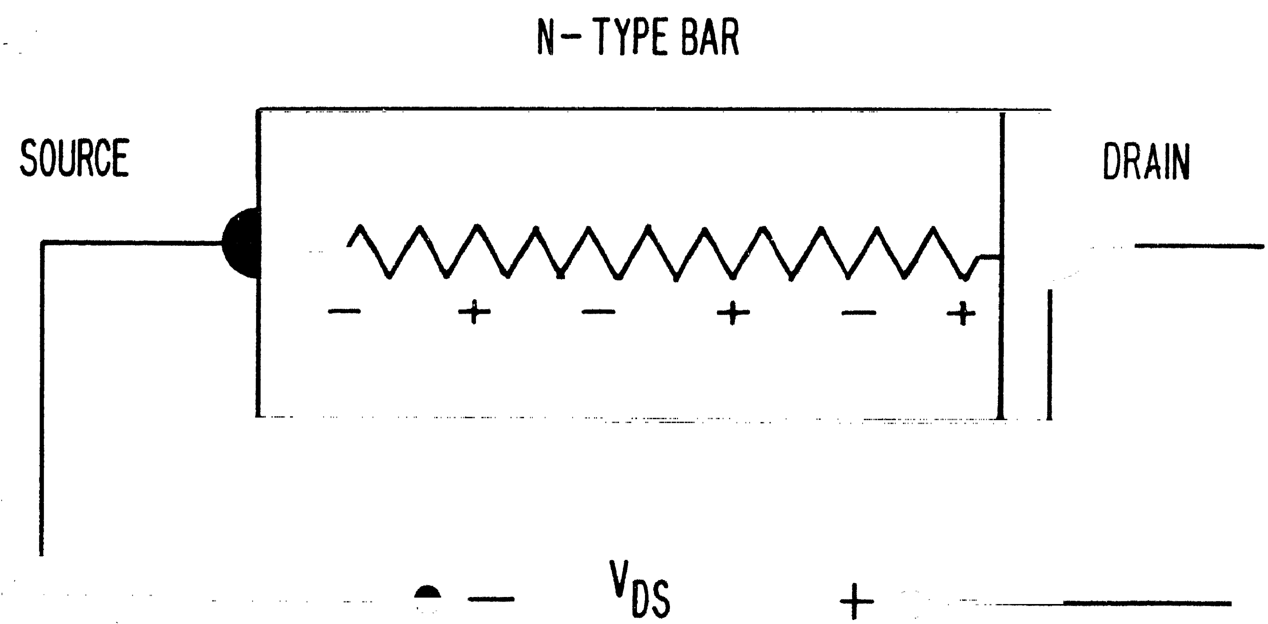
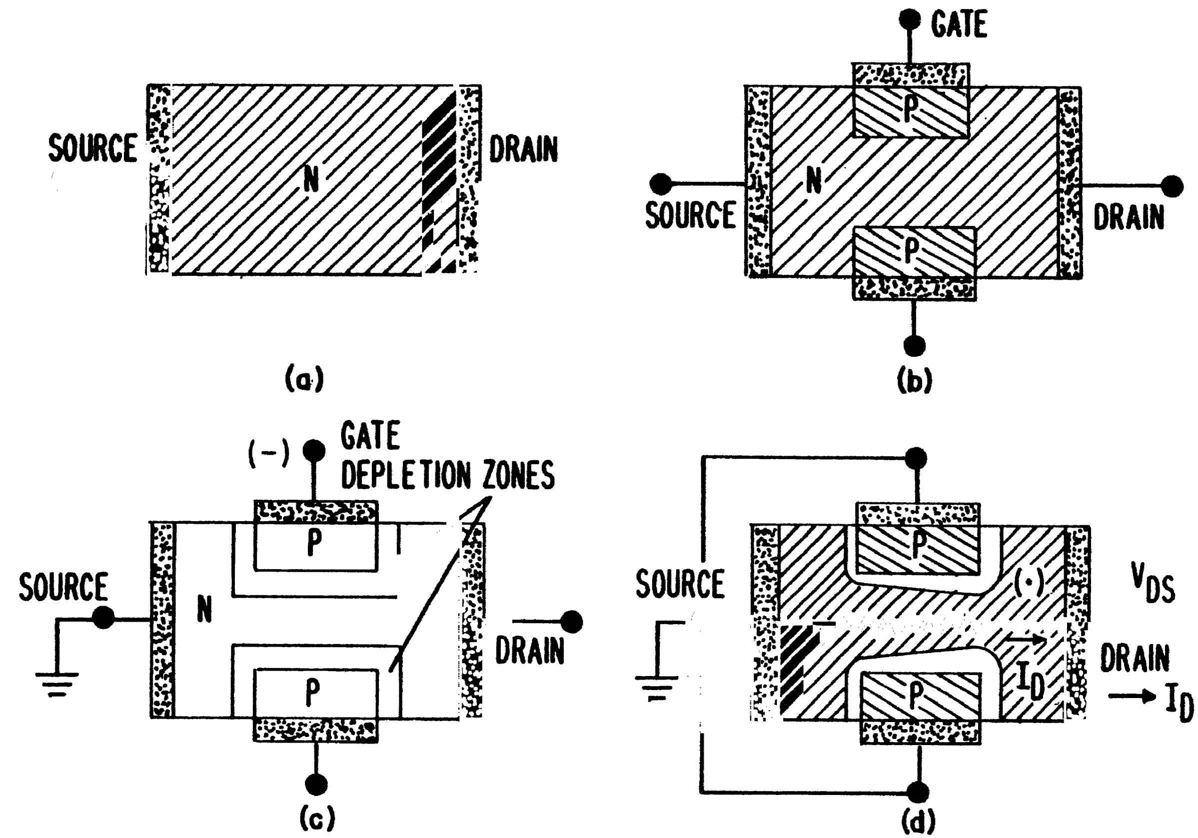


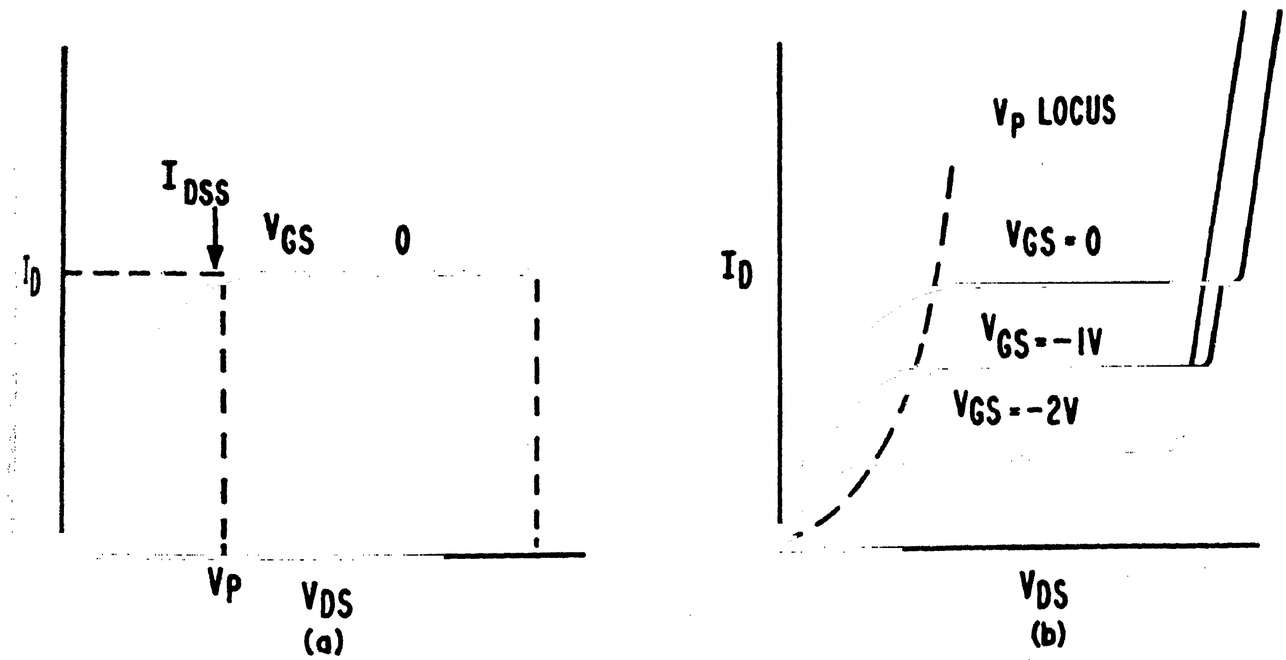
JFET CONSTRUCTION

Figure 1



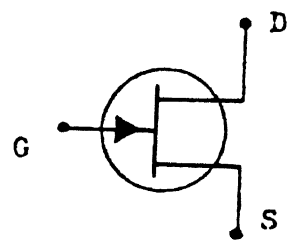
DEVELOPMENT OF JUNCTION FIELD-EFFECT TRANSISTORS

Figure 2

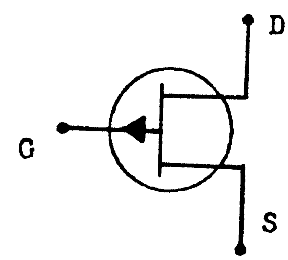


DRAIN CURRENT CHARACTERISTICS

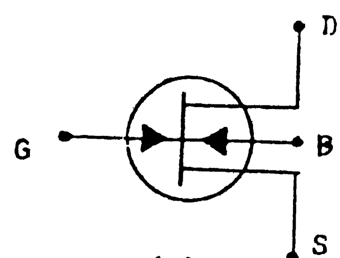
Figure 3



(a)
N-Channel

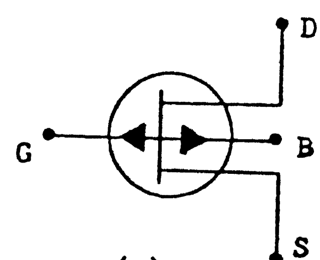


(b)
P-Channel



(c)
N-Channel

P-Substrate



(d)
P-Channel

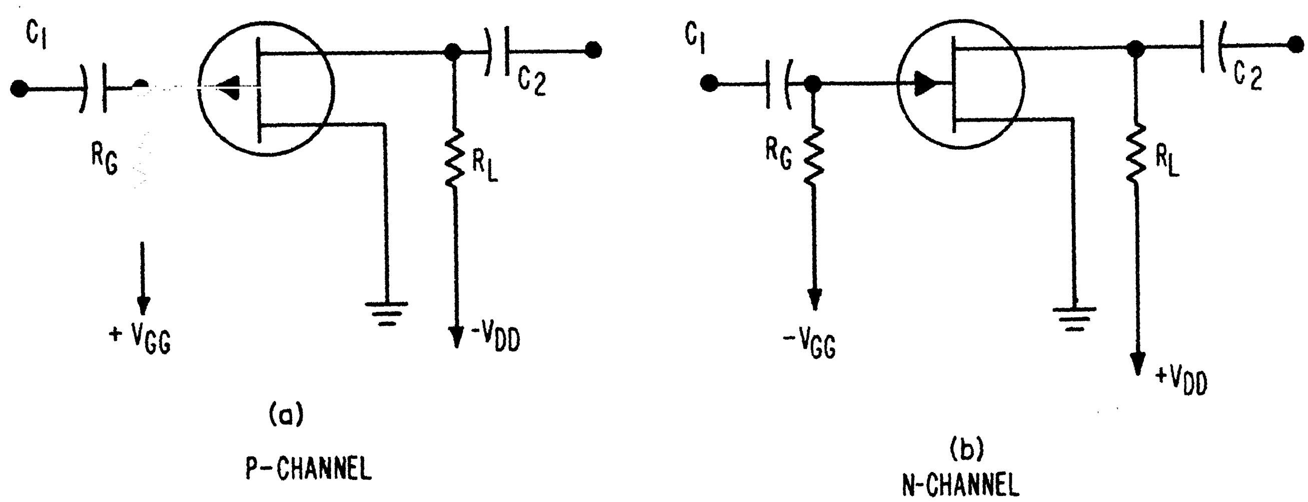
N-Substrate

JFET SYMBOLOGY

Figure 4

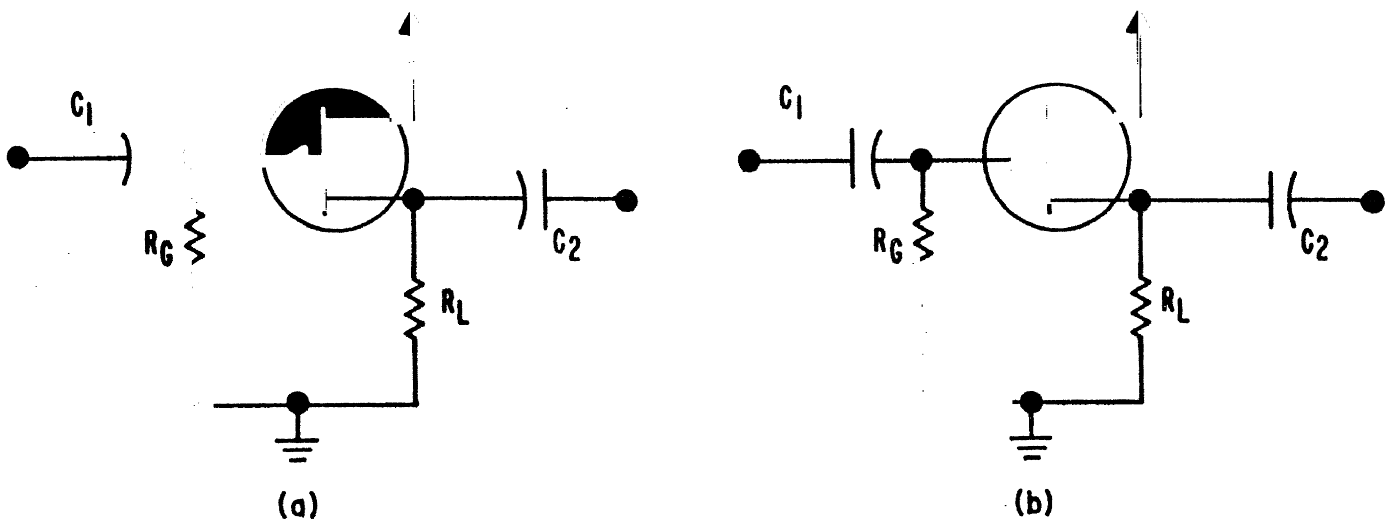
[I. JFET Symbology

III. JFET Circuits



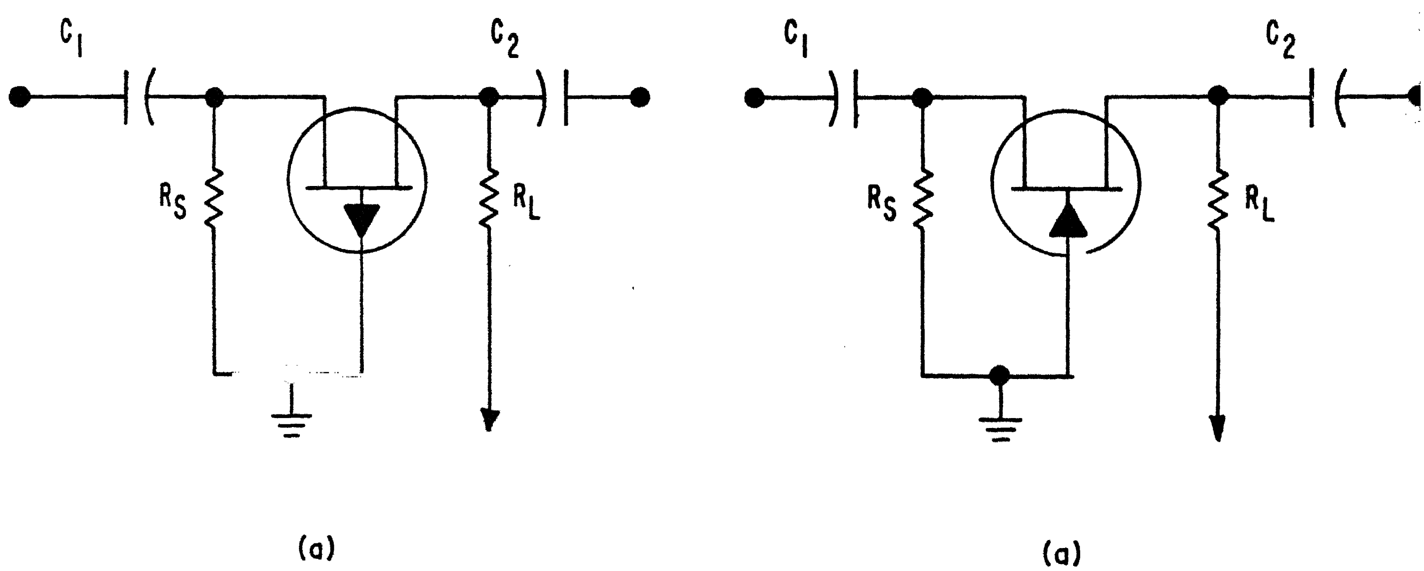
JFET COMMON SOURCE AMPLIFIER

Figure 5



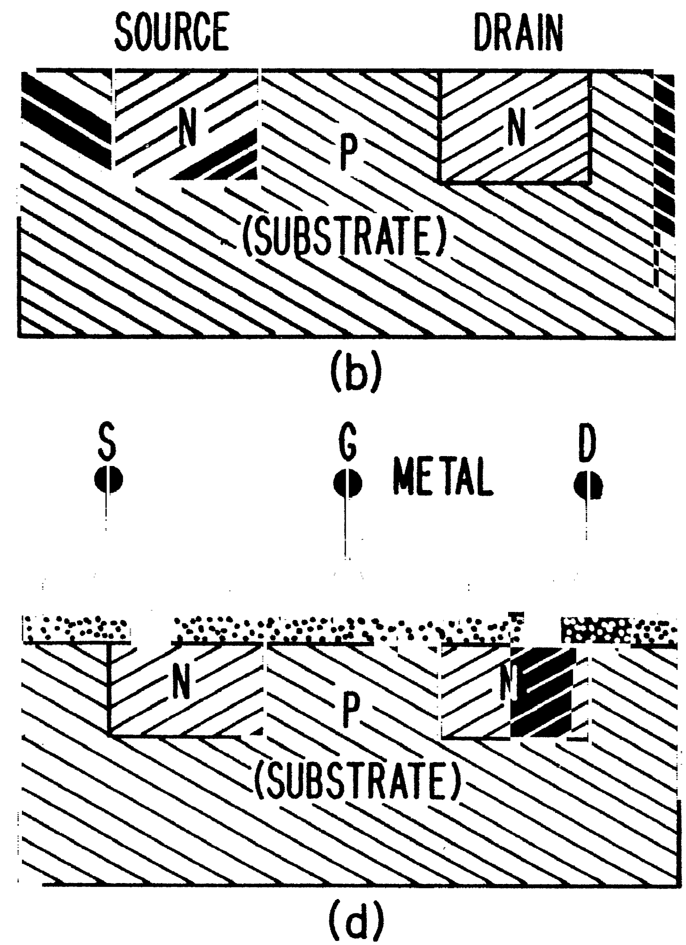
JFET CD AMPLIFIERS

Figure 6



JFET CG AMPLIFIER

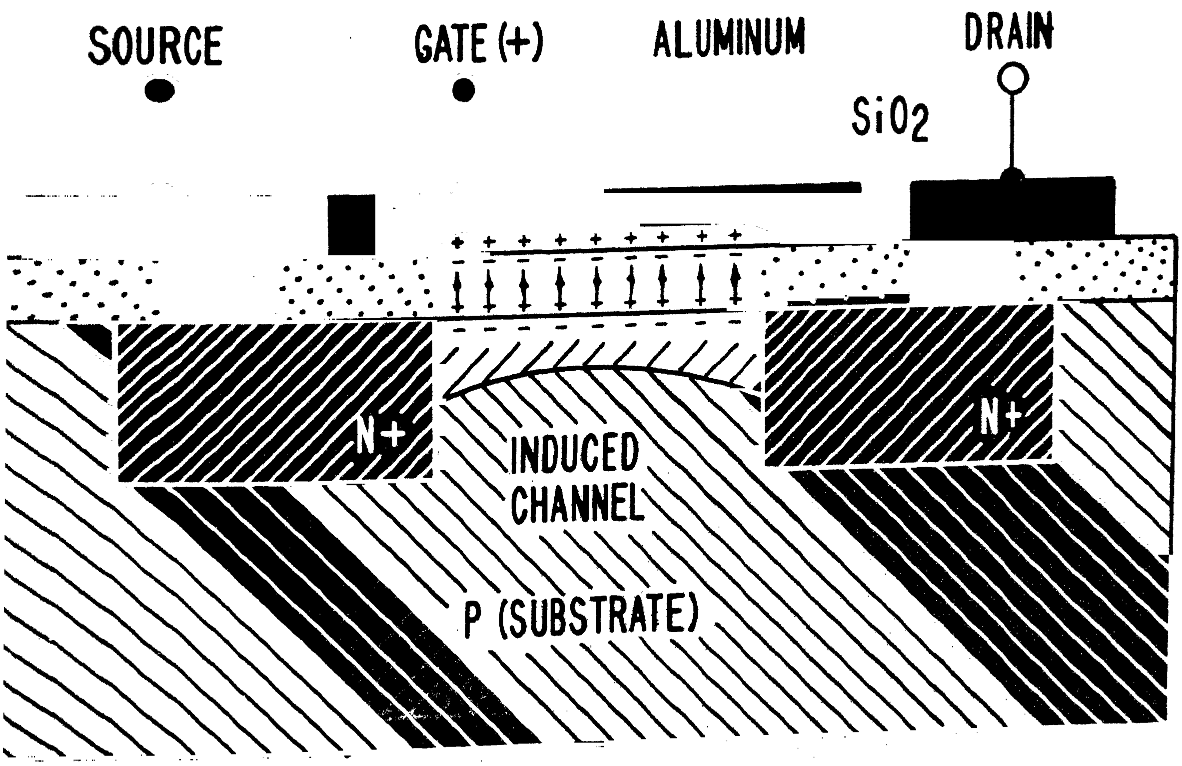
Figure 7



ENHANCEMENT MOSFET CONSTRUCTION

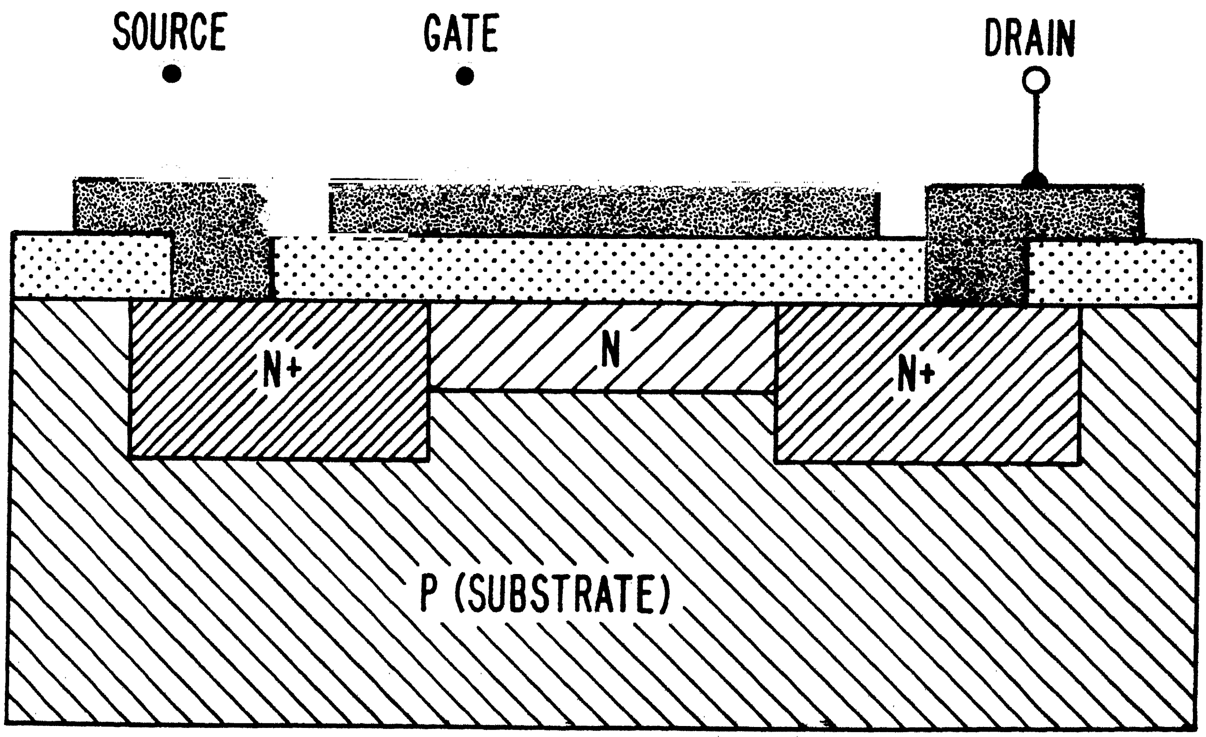
Figure 8

IV. MOSFETs



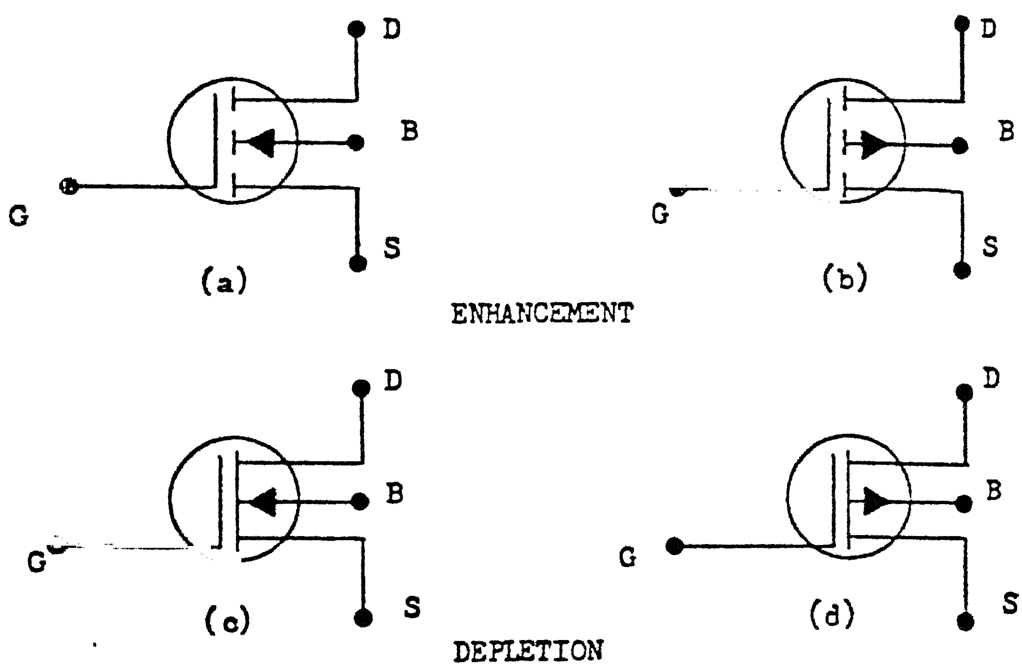
CHANNEL ENHANCEMENT

Figure 9



Depletion/Enhancement MOSFET

Figure 10



MOSFET Symbols

Figure 11

V. MOSFET Symbology

VI. Avalanche devices

A. Zener Diodes

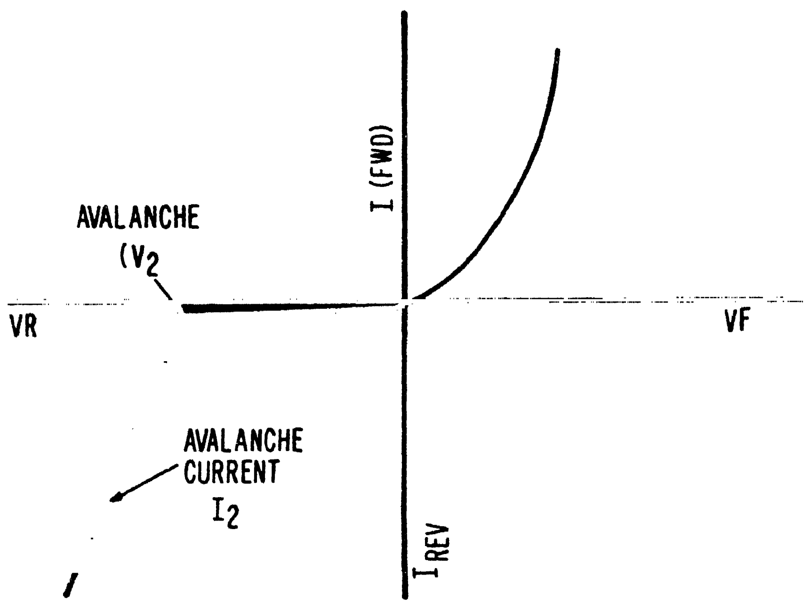


Figure 12

B. PNPN Diodes

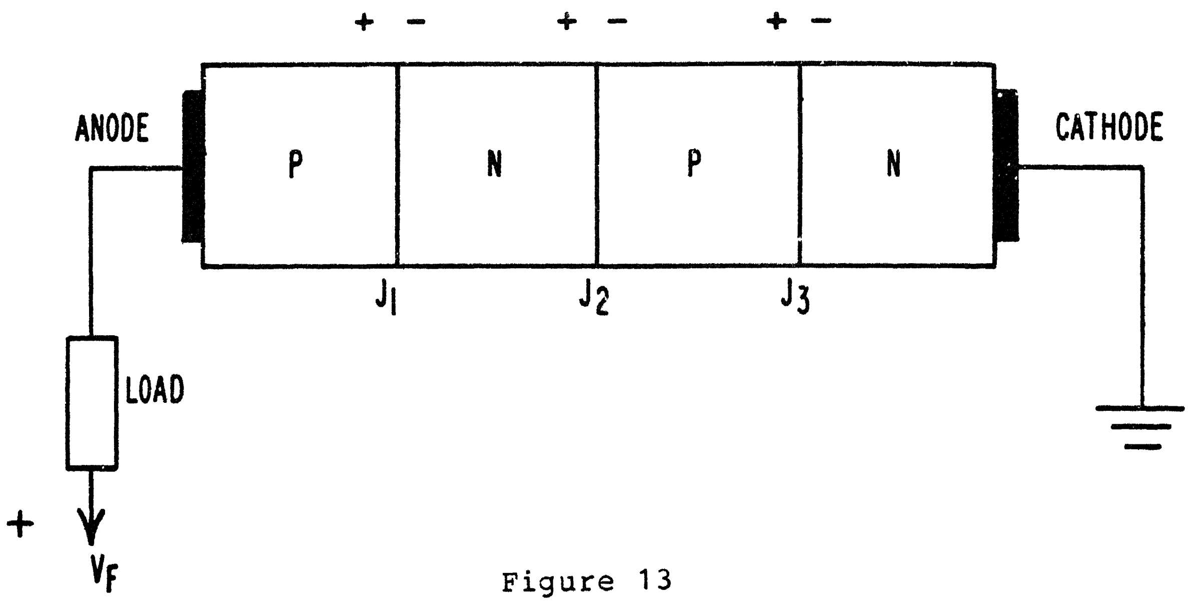
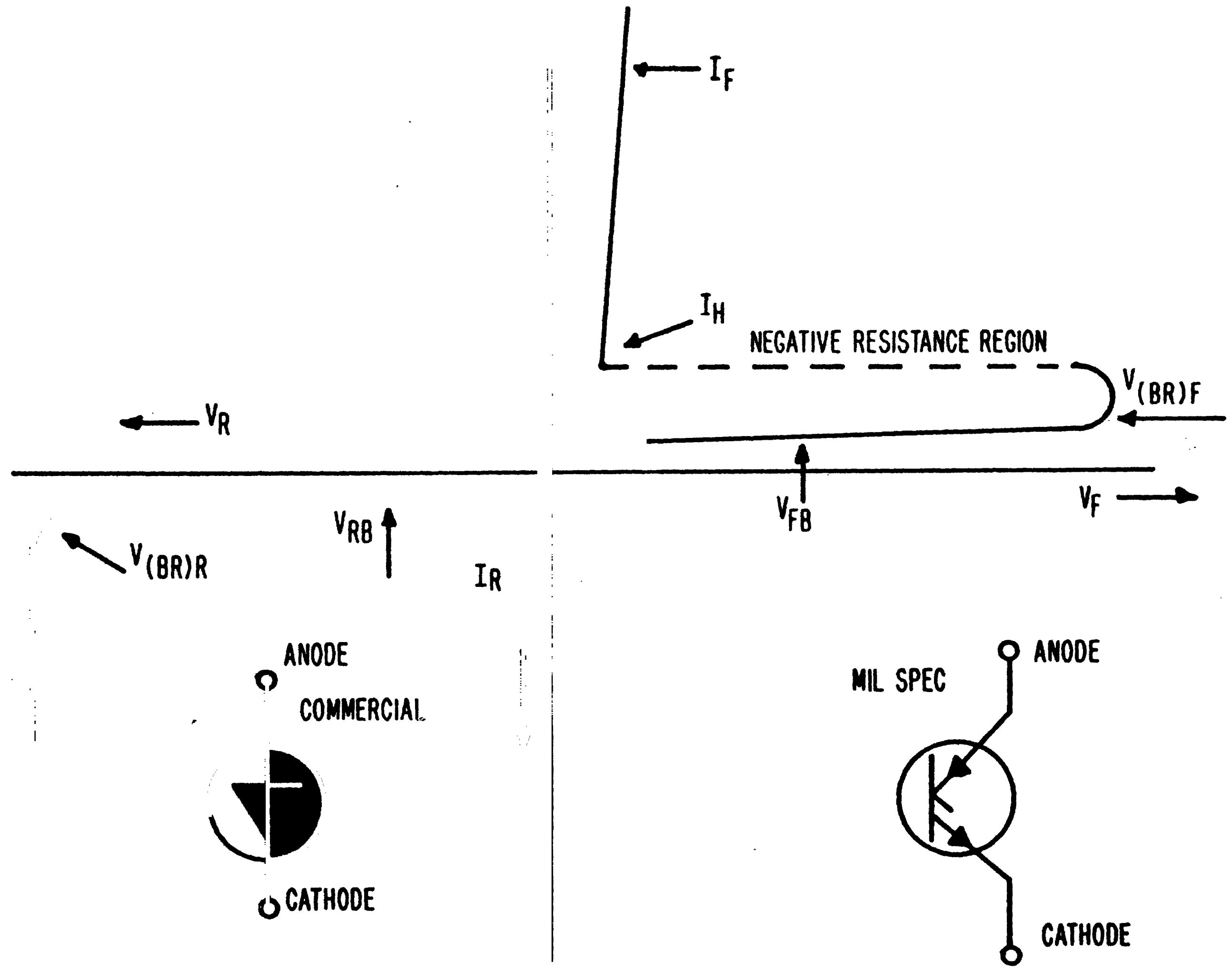


Figure 13



PNPN CHARACTERISTIC GRAPH

Figure 14

:. Silicon-Controlled Rectifiers

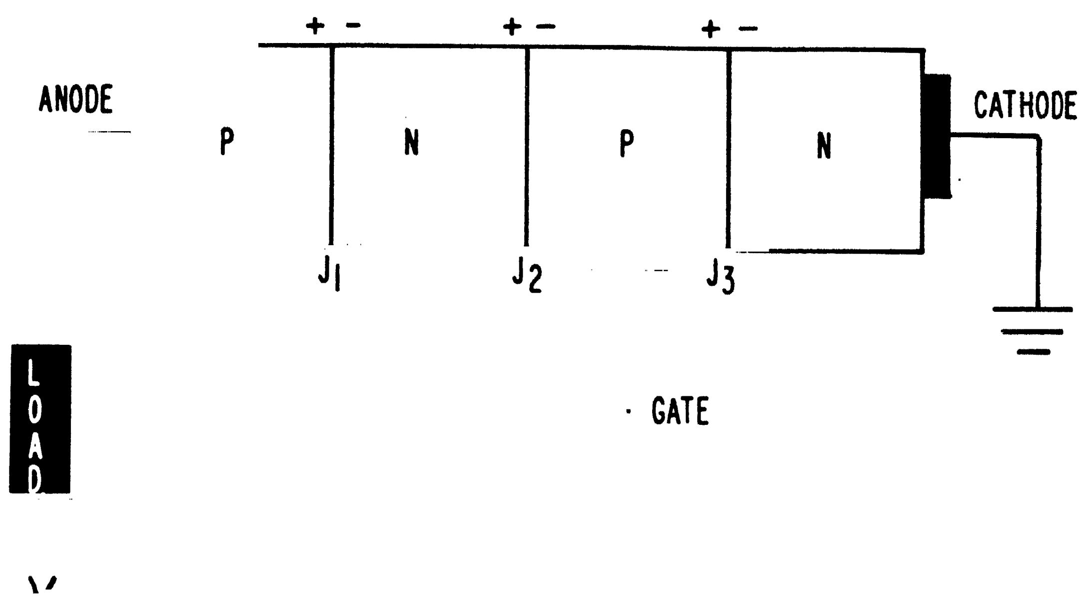


Figure 15--Silicon-Controlled Rectifier

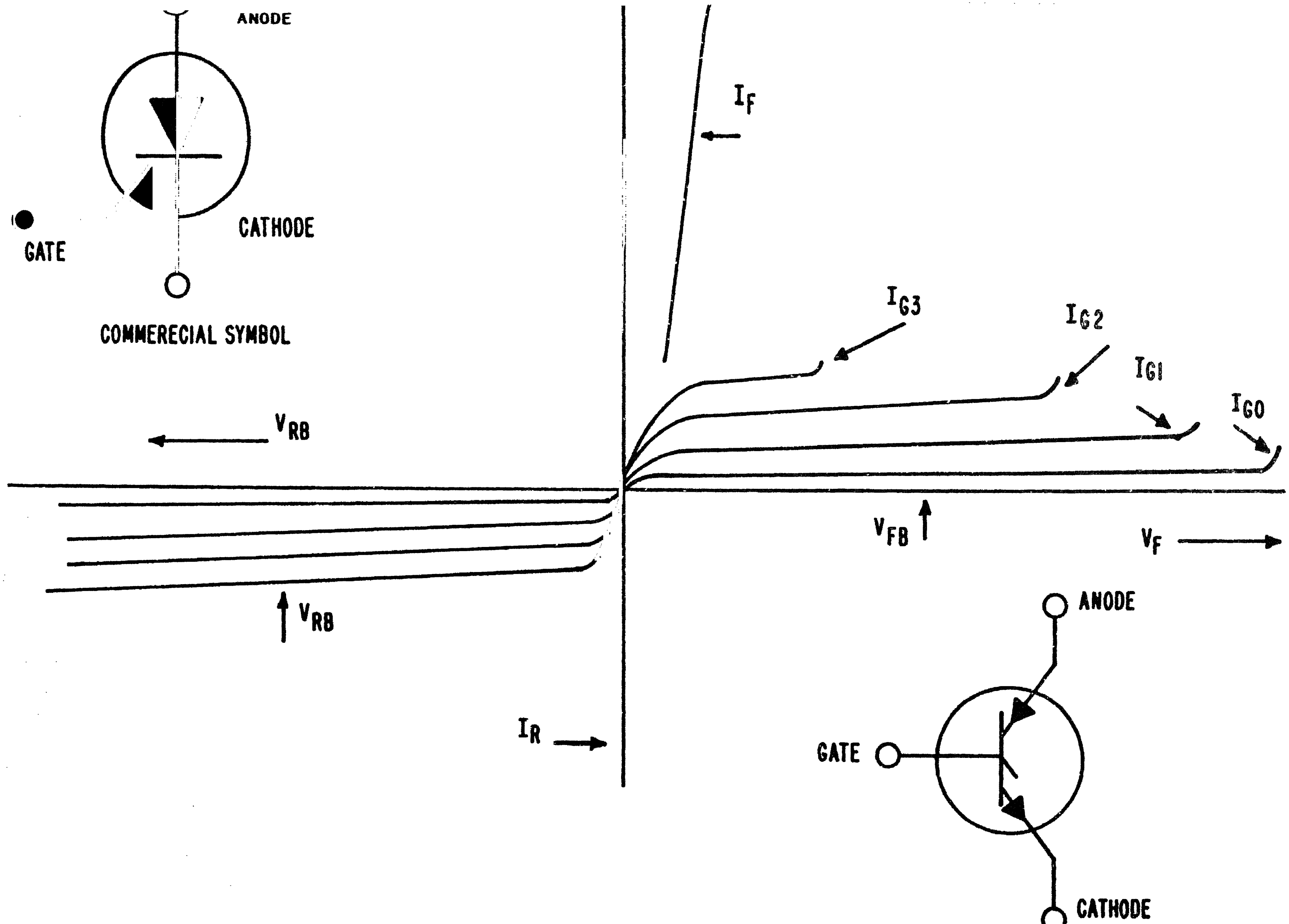

ANODE
CATHODE
GATE
COMMERECIAL SYMBOL
I_F
I_{G3}
I_{G2}
I_{G1}
I_{G0}
V_{RB}
V_{RB}
V_{FB}
V_F
I_R
ANODE
GATE
CATHODE

Figure 16

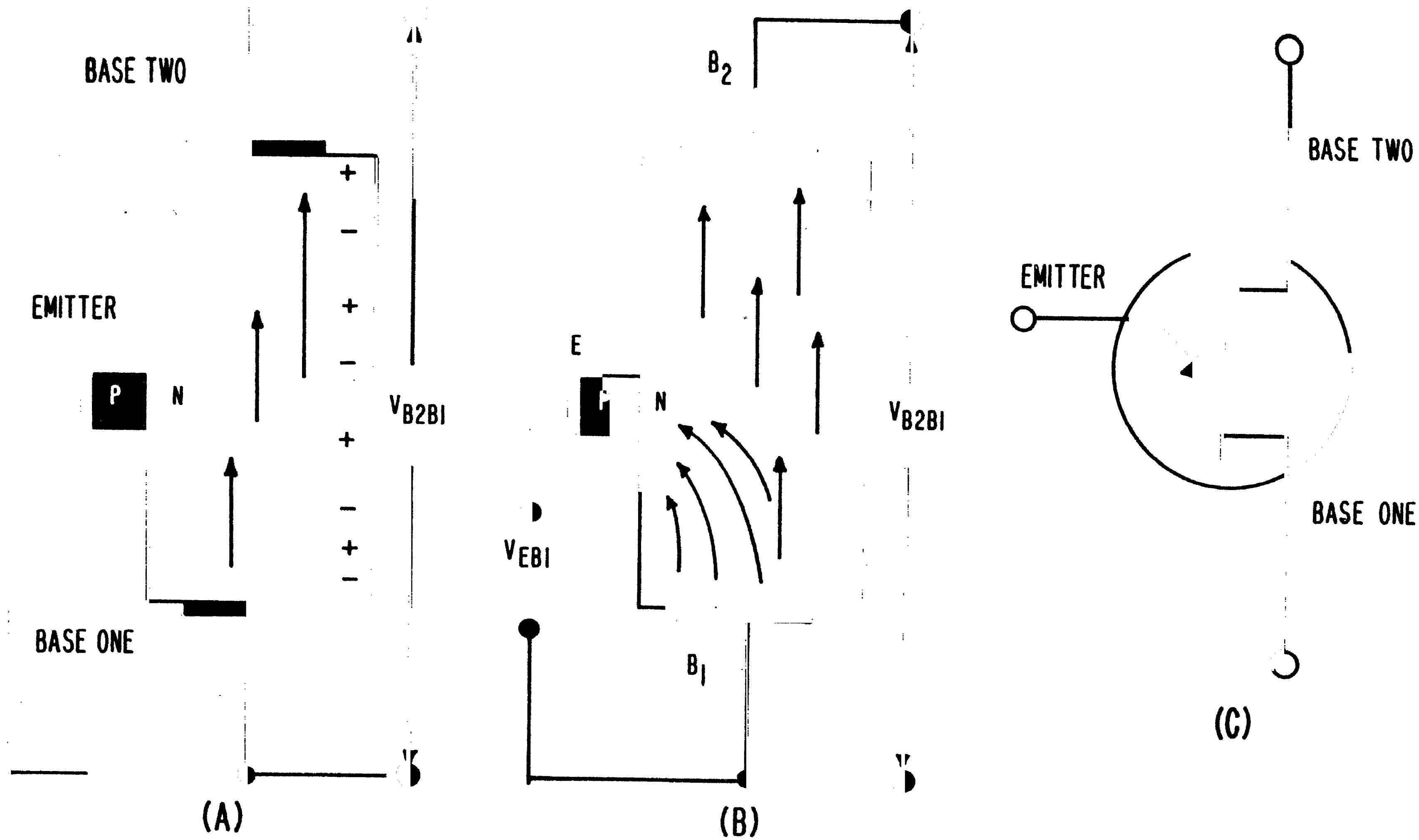

BASE TWO
EMITTER
P
N
BASE ONE
+
−
V_{B2B1}
(A)
B_2
E
N
V_{EB1}
B_1
(B)
EMITTER
BASE TWO
BASE ONE
(C)

Figure 17

NOTETAKING SHEET 2.15.1N

VACUUM TUBE FUNDAMENTALS

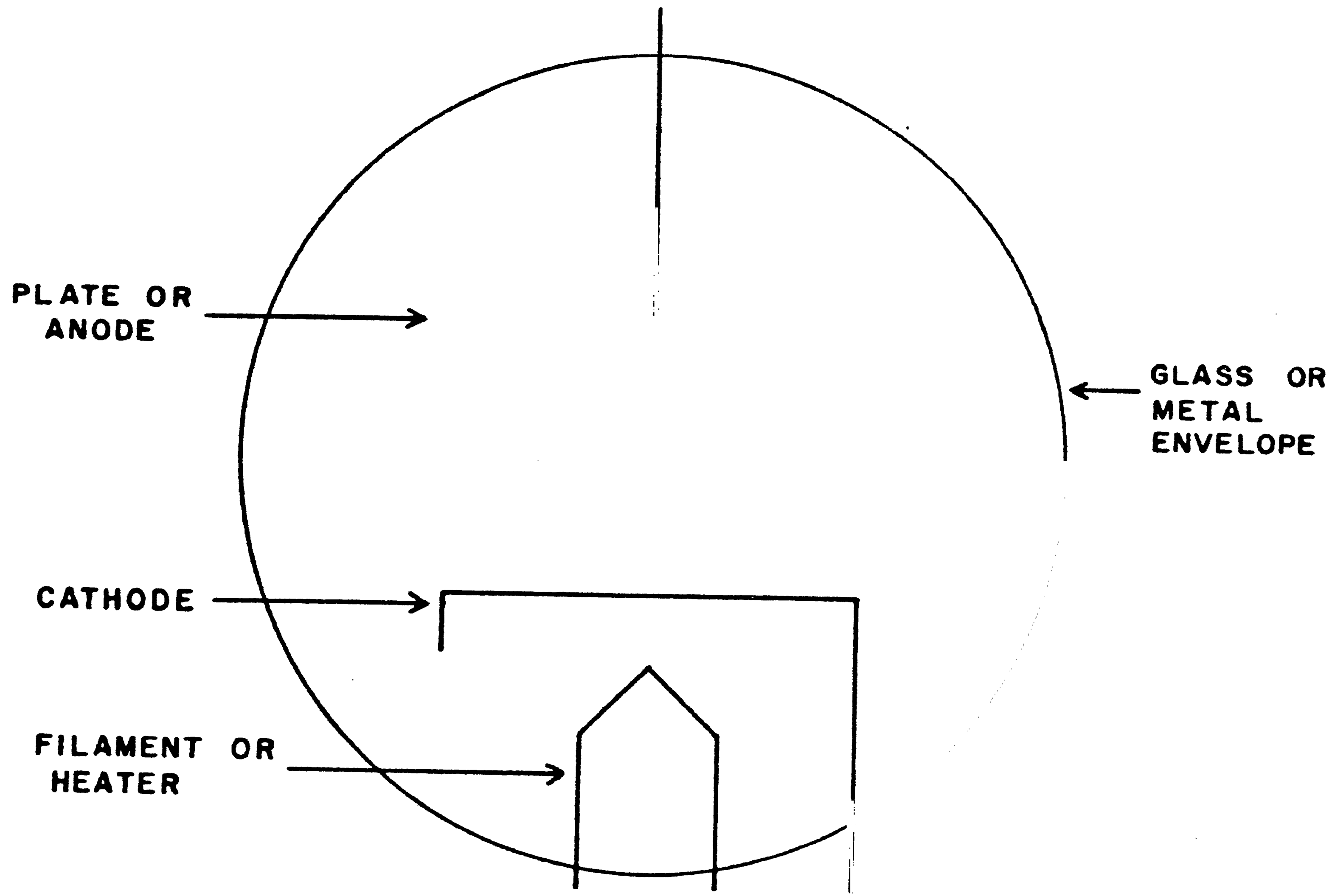
EFERENCES:

. Basic Electronics, Vol. 1, NAVPERS 10087-C, Chapter 7, pages 143 to 172.

. Electronic Circuit Analysis, Vol. I, NA 00-80-T-79, Chapter 4, pages 4-1 to 4-42.

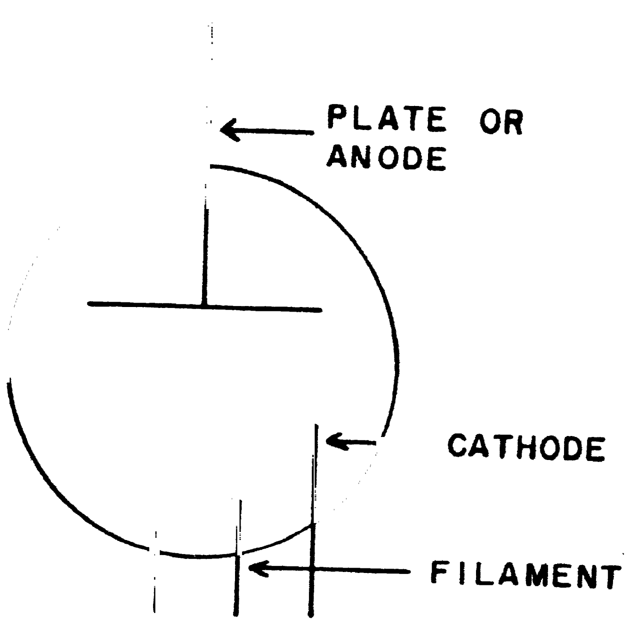
TETAKING OUTLINE

I. Basic Construction of a Vacuum Tube.



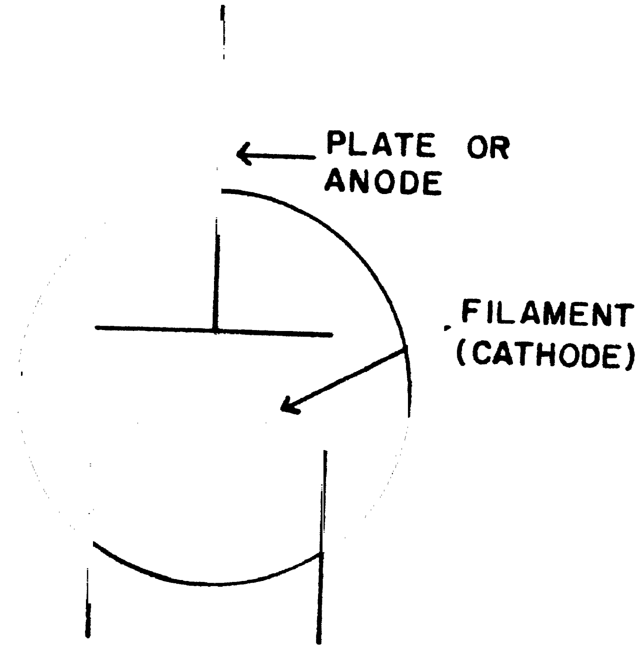
BASIC CONSTRUCTION OF A VACUUM TUBE

Figure 1



INDIRECTLY HEATED CATHODE

Figure 3



DIRECTLY HEATED CATHODE

Figure 2

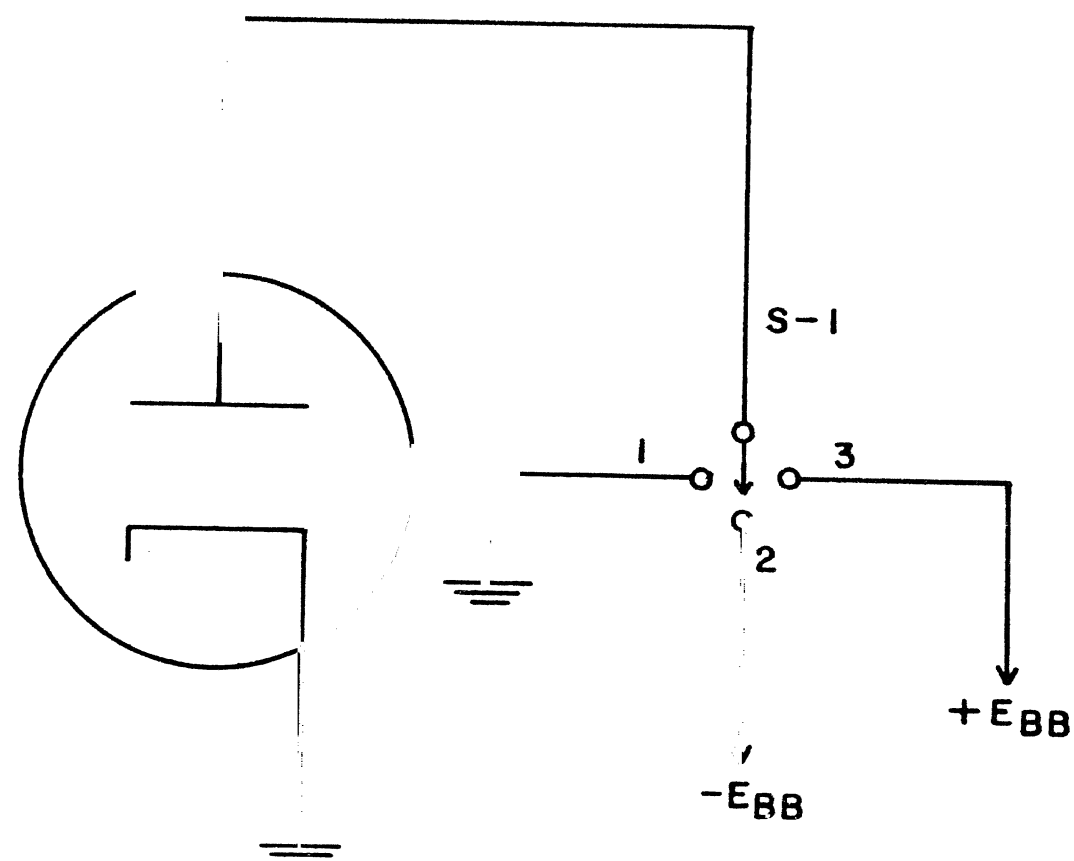
[. Types of Emission

A. Thermionic or thermal emission

B. Photoelectric emission

C. Cold cathode emission

III. Tube Operation



DIODE VACUUM TUBE

Figure 4

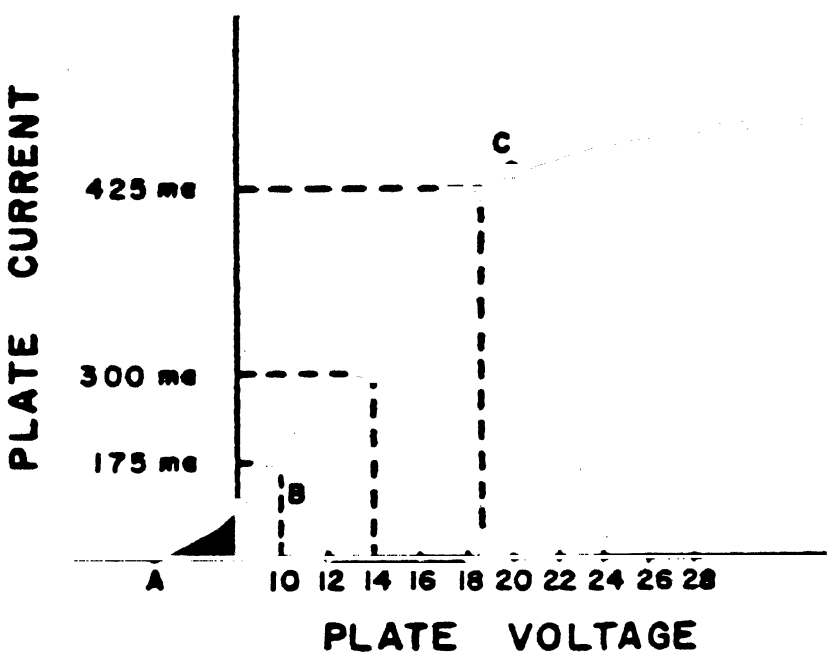


PLATE CURRENT
425 ma
300 ma
175 ma
C
B
A
10 12 14 16 18 20 22 24 26 28
PLATE VOLTAGE

Figure 5

Diode Vacuum Tube Circuit

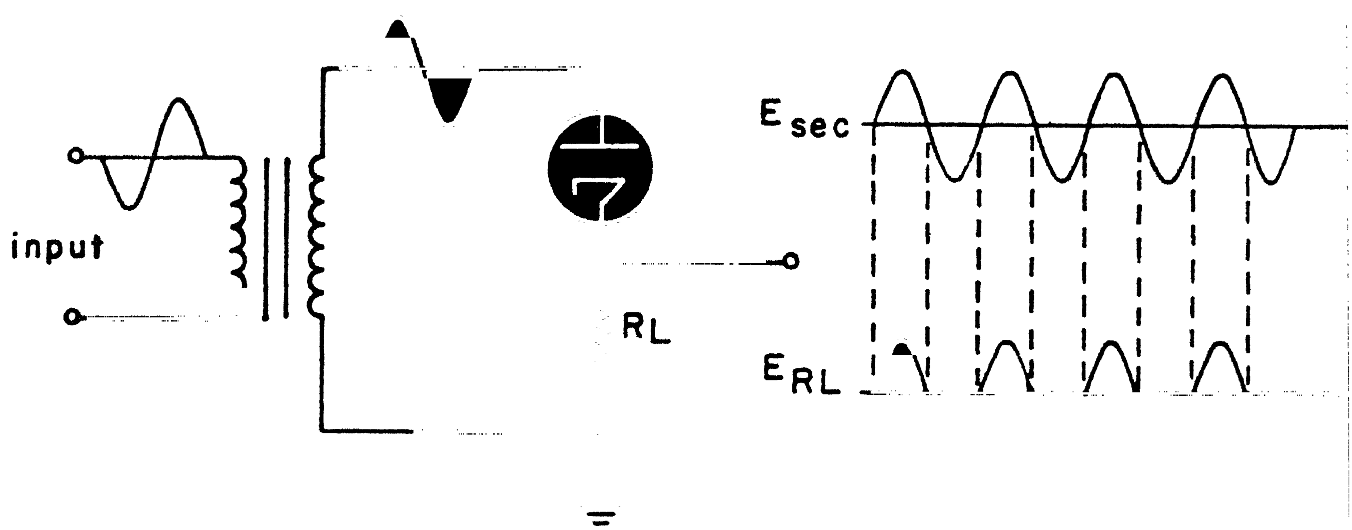


Figure 6 - Diode Vacuum Tube Half-Wave Rectifier.

NOTETAKING SHEET 2.16.1N

TRIODES

REFERENCES:

1. Electronic Circuit Analysis, NA 00-80-T-79, Chapter 4, pages 4-1 to 4-22.

2. Basic Electronics, Vol. I, NAVPERS 10087-C, Chapter 7, pages 143 to 172.

3. Robert L. Shrader, Electronic Communication, Chapter 9, Fourth Edition. 1980, McGraw-Hill Book Company Inc.

NOTETAKING OUTLINE

I. Construction of a Triode Vacuum Tube

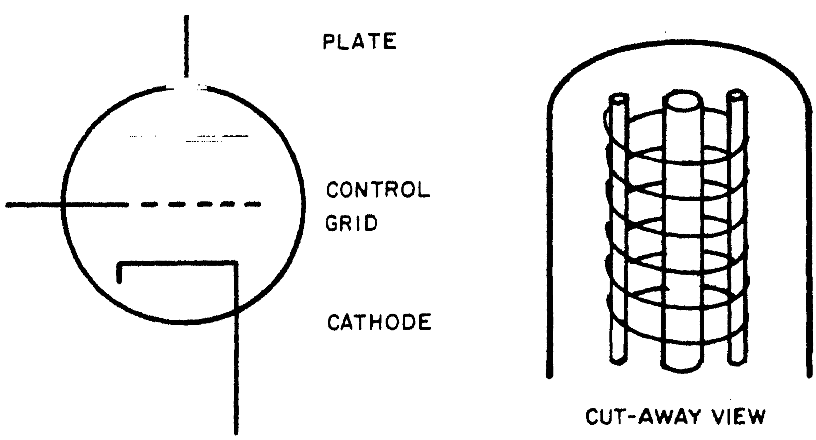


Figure 1 - Triode Vacuum Tube

II. Bias

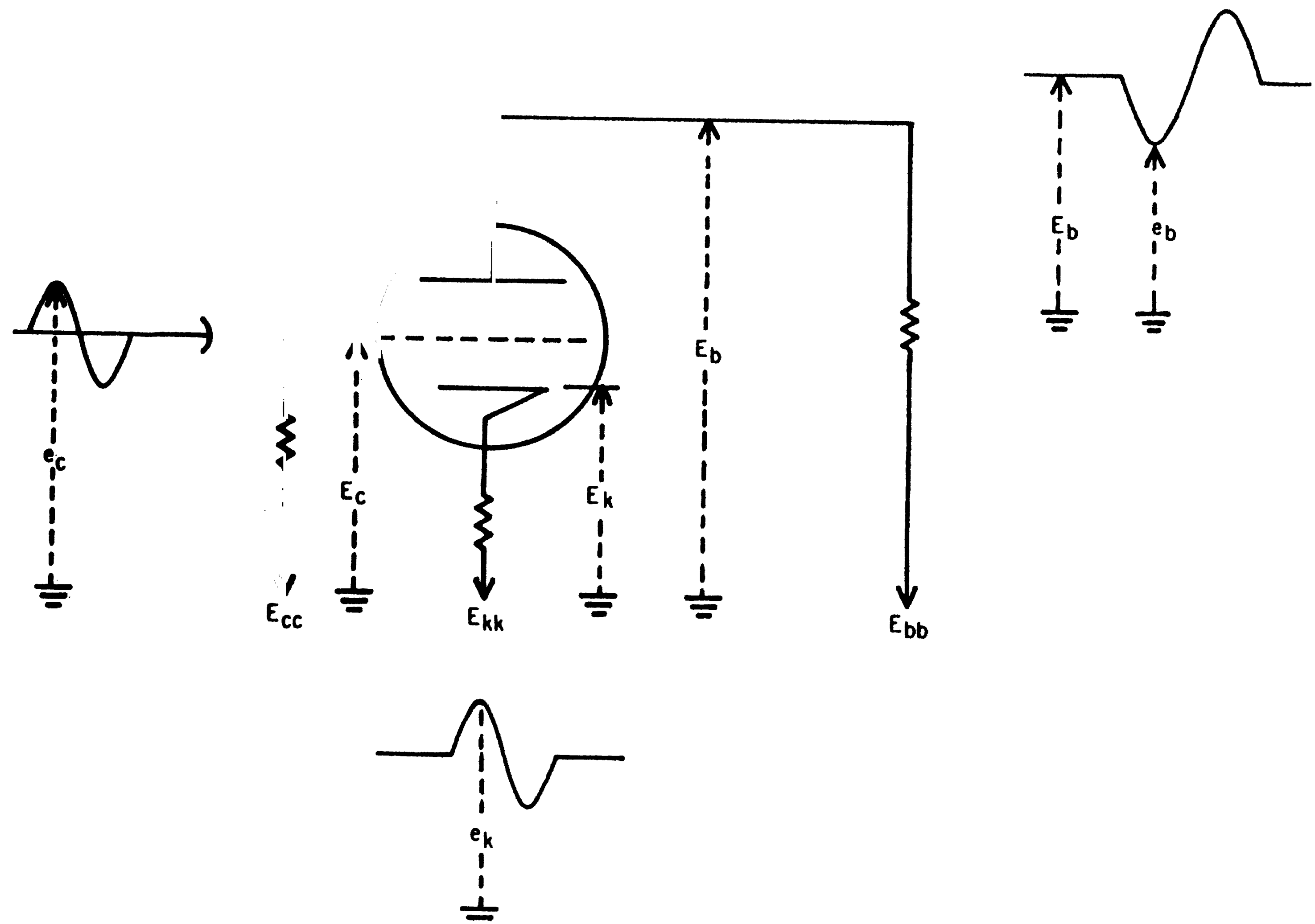


Figure 2 - Vacuum Tube Notations

II. Electron Tube Notations

IV. Vacuum Tube Static Characteristic Curves

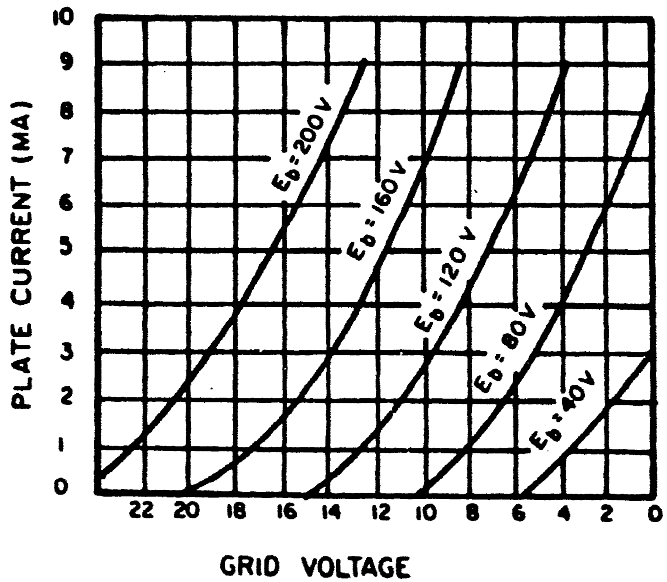


Figure 3 E_c-I_b GRID FAMILY OF CURVES

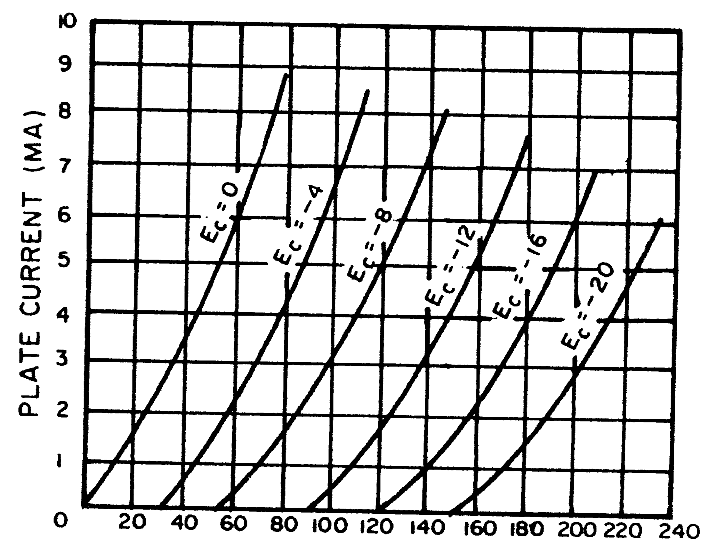


Figure 4 - E_b - I_b Plate Family Curves

E. Dynamic Characteristics of a Triode

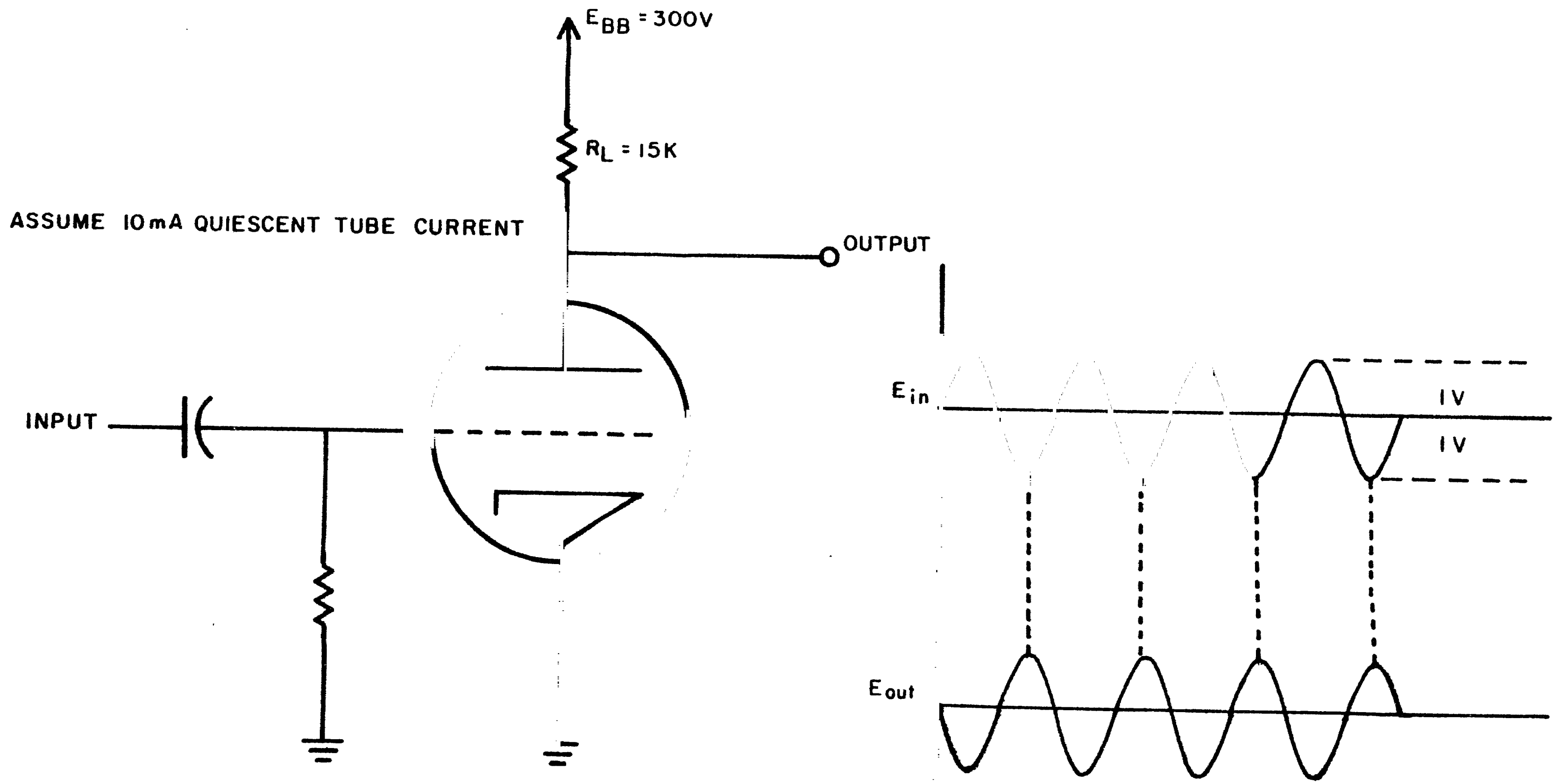

$E_{BB} = 300V$
$R_L = 15K$
ASSUME 10mA QUIESCENT TUBE CURRENT
OUTPUT
INPUT
E_{in}
1V
1V
E_{out}

Figure 5

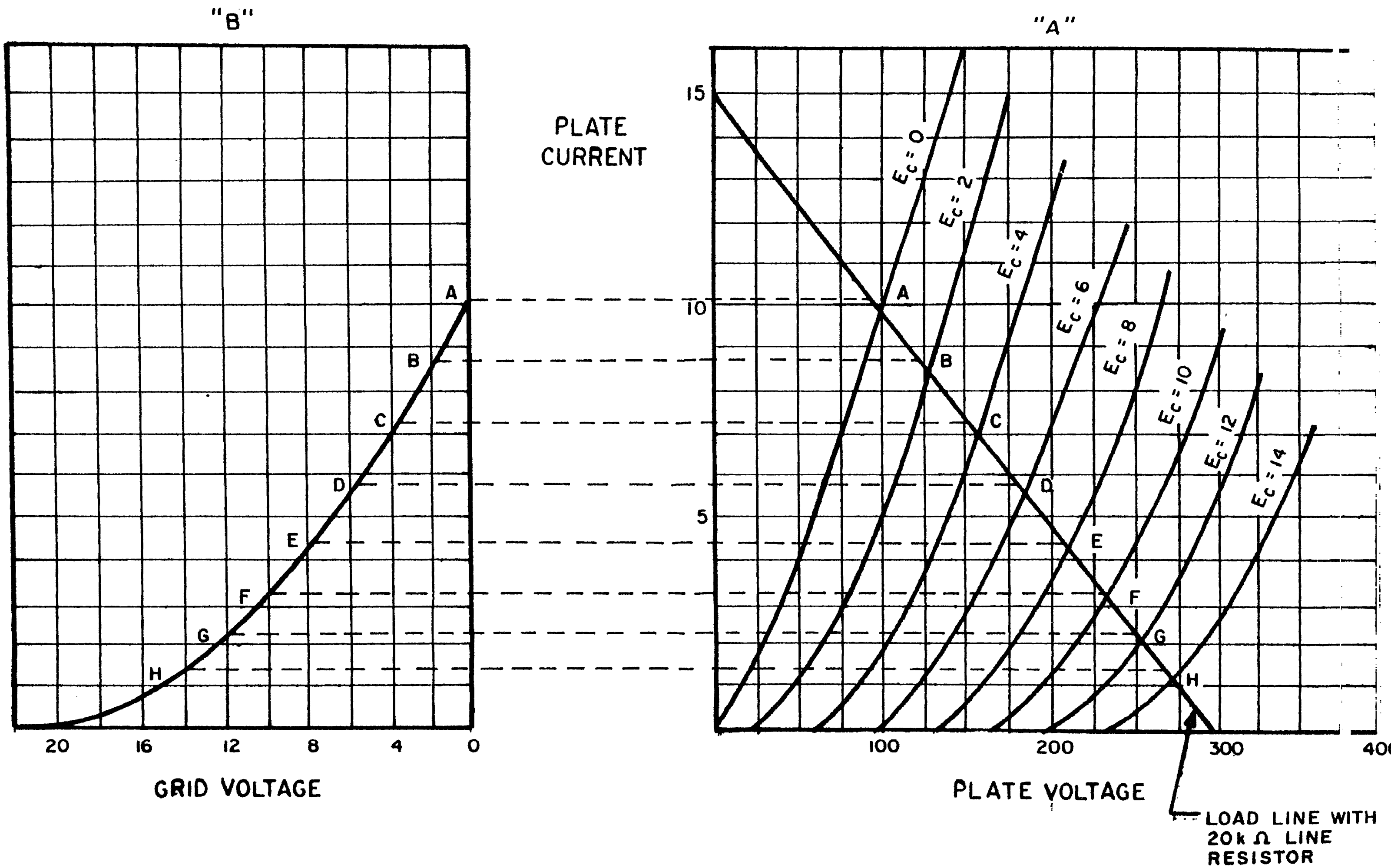


Figure 6 DYNAMIC TRANSFER CURVE (D.T.C.)

VI. The Dynamic Transfer Curve (DTC)

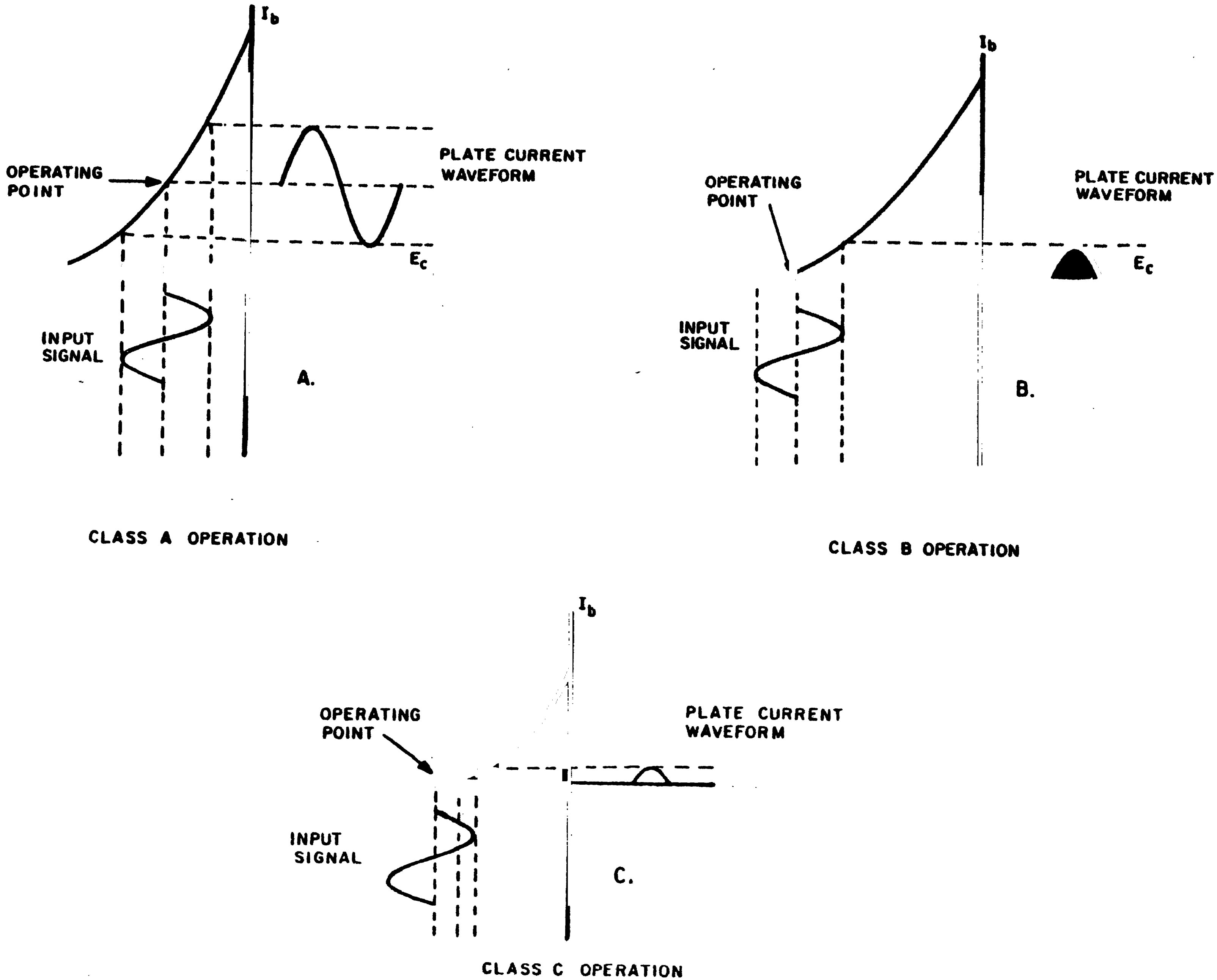


Figure 7 DYNAMIC TRANSFER CURVE USES

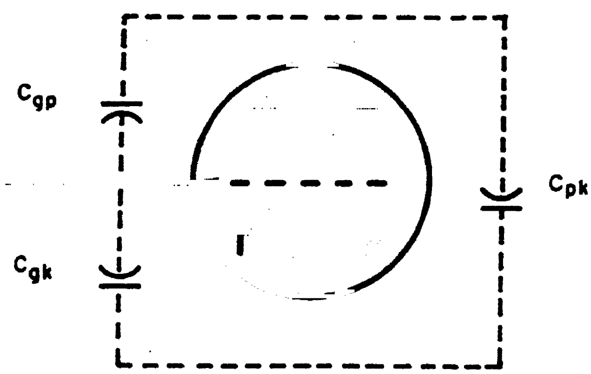


Figure 8 - Interelectrode Capacitance

VII. Limitations of the Triode

NOTETAKING SHEET 2.17.1N

MULTIELEMENT TUBES

REFERENCES:

1. Electronic Circuit Analysis, Vol. I, NA 00-80-T-79, Chapter 4, pages 4-1 to 172.

2. Basic Electronics, Vol. I, NAVPERS 10087-C, Chapter 7, pages 143 to 172.

3. Robert L. Shrader, Electronic Communication, Chapter 9, Fourth edition. 1980, McGraw-Hill Book Company Inc.

NOTETAKING OUTLINE:

I. Tetrodes

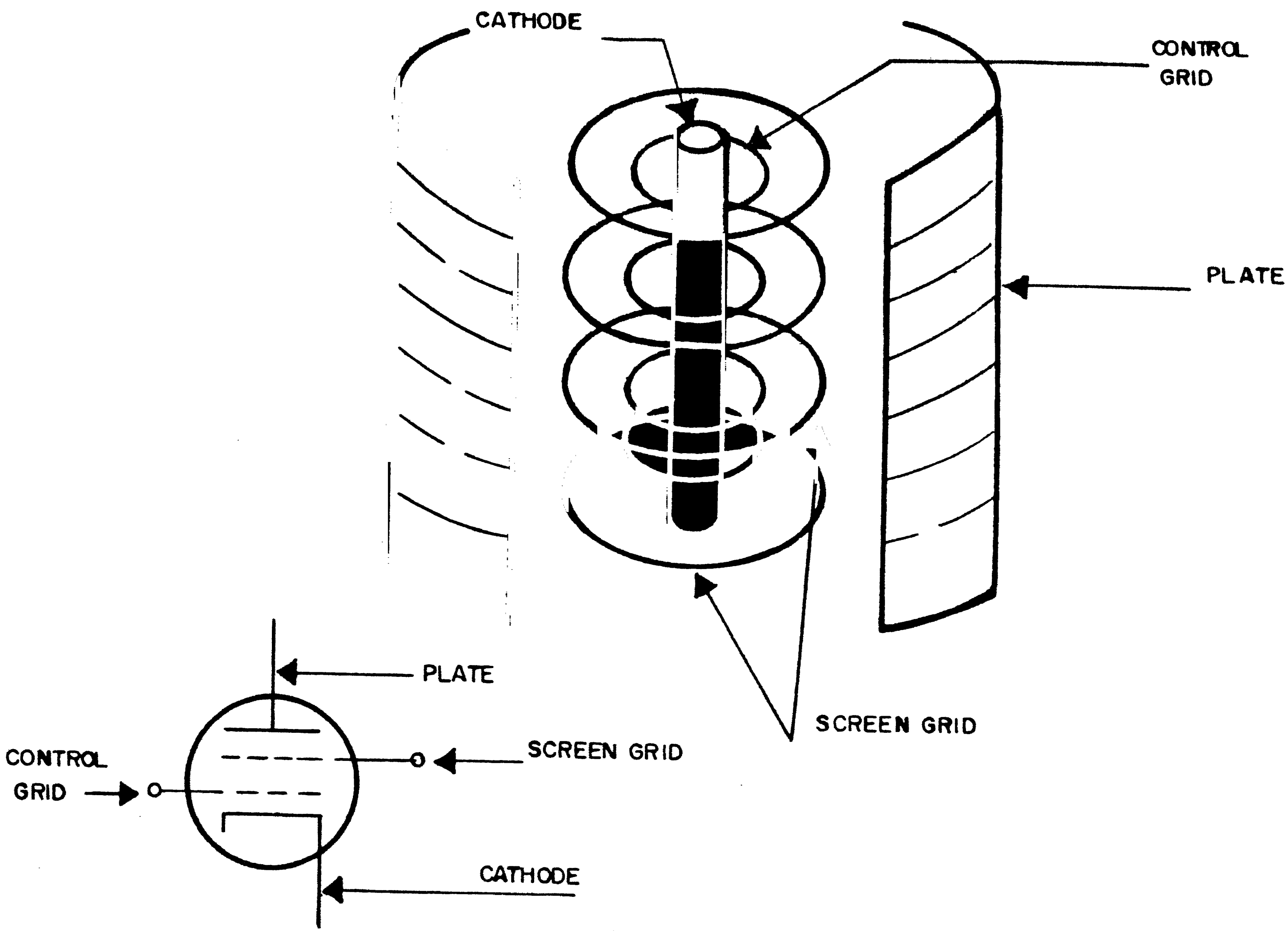


Figure 1 - TETRODE VACUUM TUBE

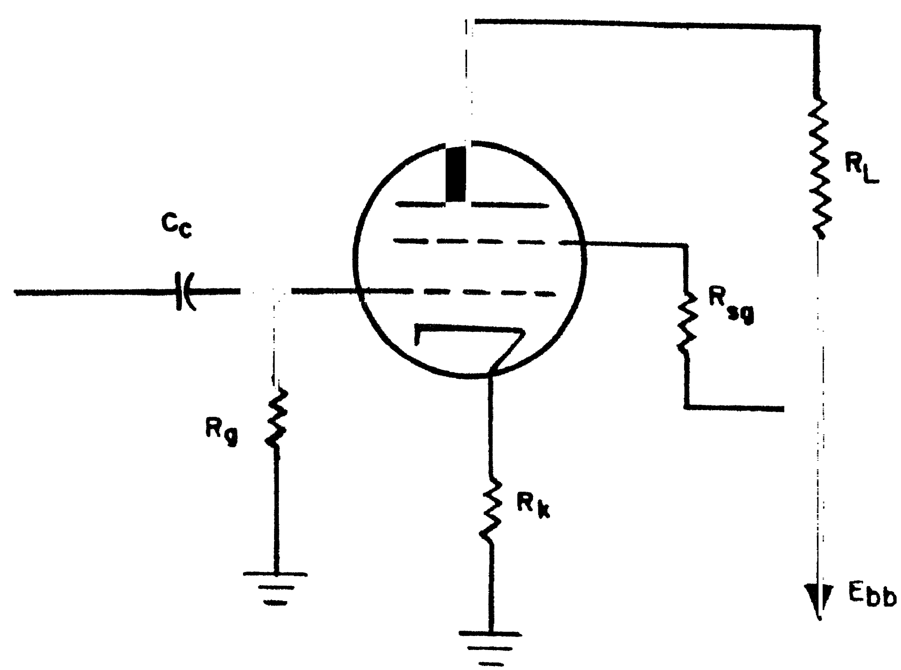


Figure 2 - TETRODE CIRCUIT

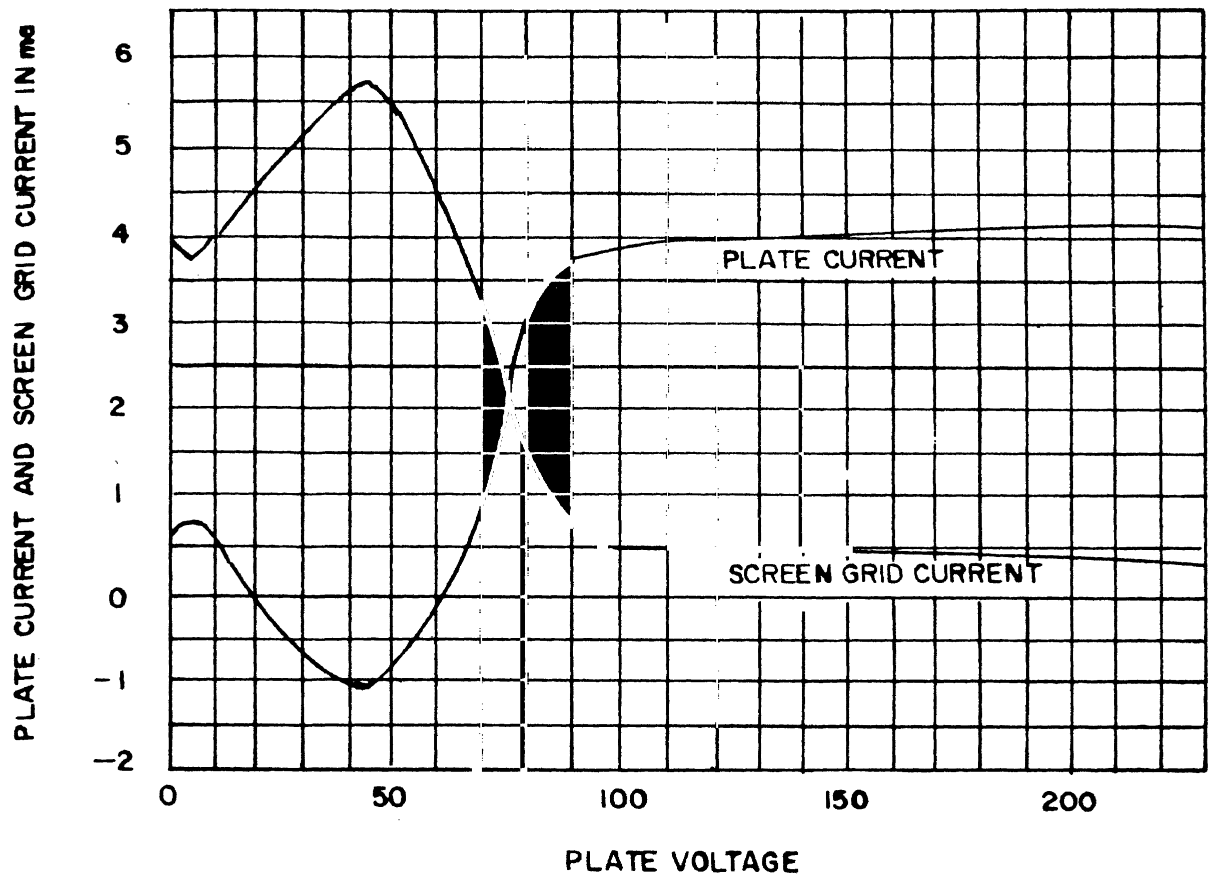


Figure 3 — TETRODE CURRENT CURVE

II. Pentodes

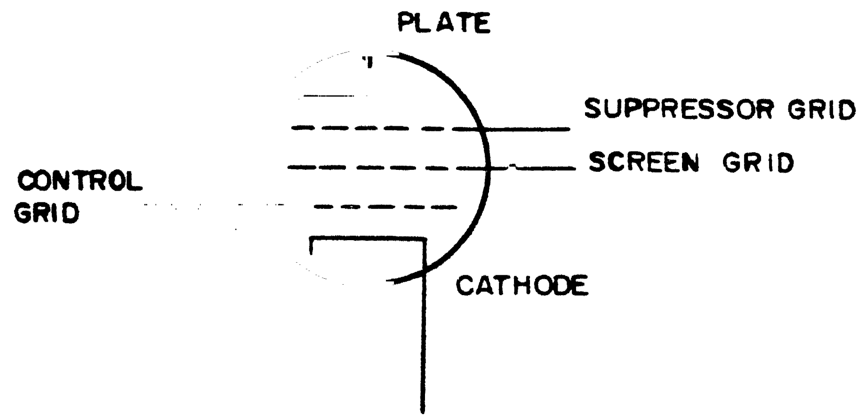


Figure 4 - PENTODE VACUUM TUBE

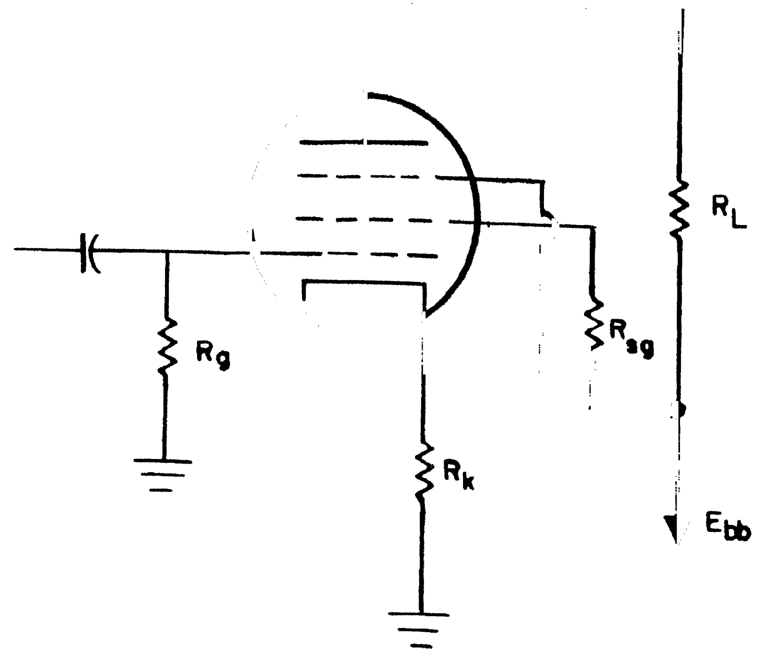


Figure 5 - PENTODE VACUUM TUBE CIRCUIT

III. Beam--Power Tubes

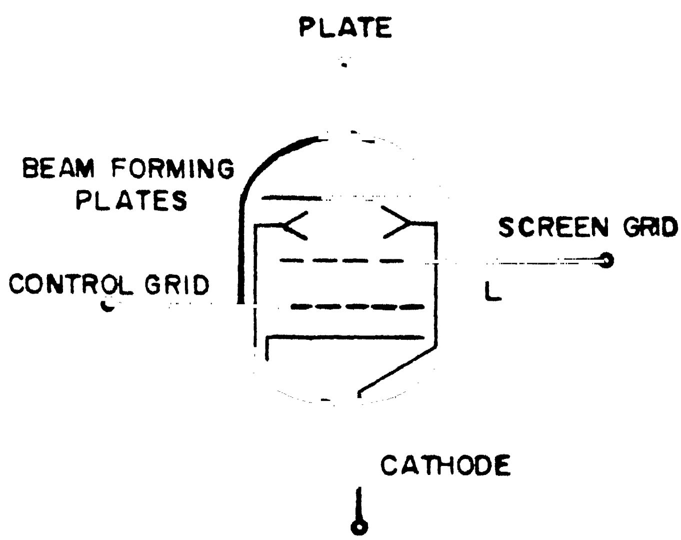


Figure 6 - Beam-Power Tube Schematic Symbol

IV. Cathode-Ray Tubes

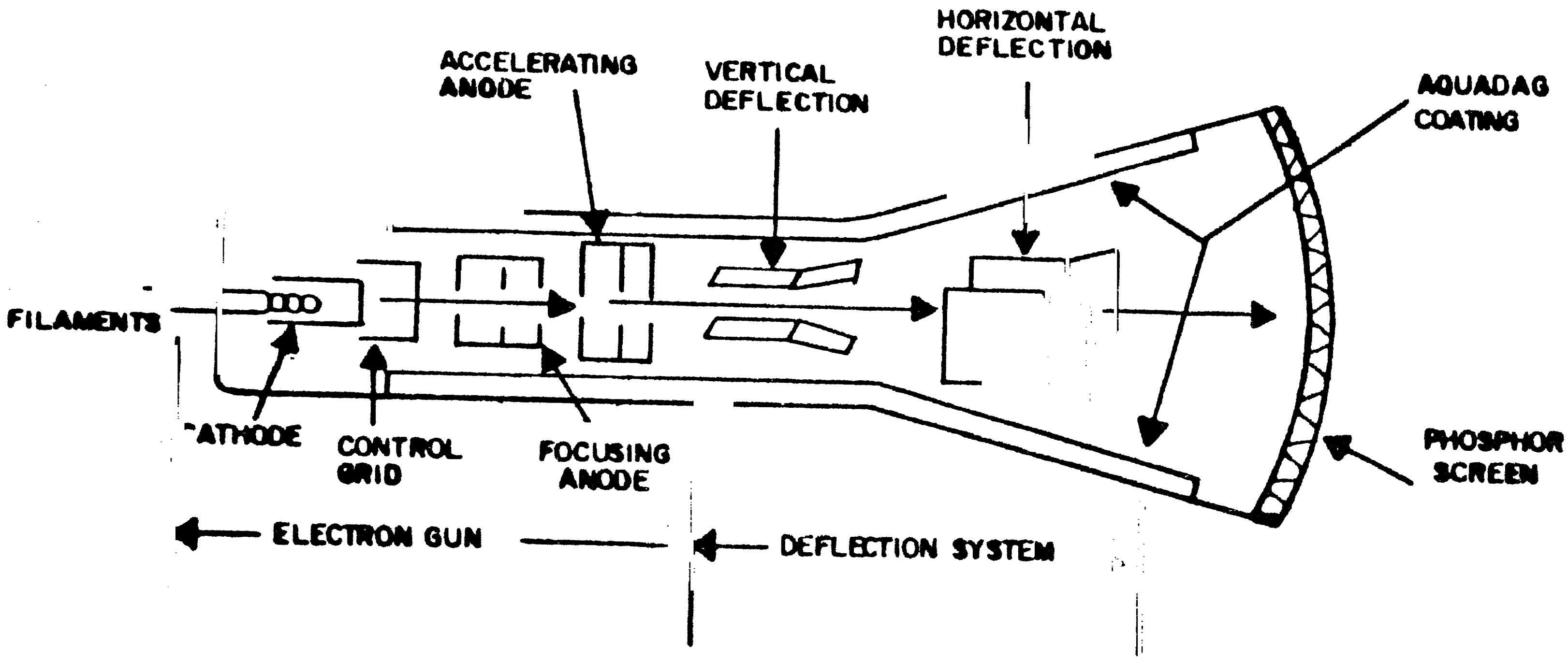


Figure 7- CATHODE RAY TUBE

FORMULA SHEET

Reactance

1. $X_L = 2\pi fL$
2. $X_C = \frac{1}{2\pi fC}$

Series Only

1. $Z_O = R$
2. E_{XL} or $E_{XC} = QE_A$

Parallel Only

1. $Z_T = \frac{Z_1 Z_2}{Z_1 + Z_2}$
2. $Z_O = \frac{E_A}{I_{line}}$
3. $Z_O = QX_L$
4. $Z_O = Q^2 R$
5. $Z_O = \left(\frac{X_L}{R}\right)^2$
6. $Z_O = \frac{L}{RC}$
7. $I_{tank} = QI_{line}$
8. $P_t = P_a \cos\theta$
9. $P_f = \frac{P_t}{P_a} = \cos\theta$

Series and Parallel Resonance

1. $F_O = \frac{1}{2\pi\sqrt{LC}}$
2. $Q = \frac{X_L}{R}$

Series and Parallel Resonance (Cont'd)

3. $NE = \frac{F_O}{Q}$
4. $BW = \frac{R}{2\pi L}$
5. $X_L = X_C = L/C$
6. $F_O = \frac{X_L}{2\pi L}$

Common Emitter Amplifier

1. $\beta = \frac{I_C}{I_B}$
2. $\beta = \frac{\alpha}{1 - \alpha}$
3. $I_{CEO} = I_{CBO}(\beta + 1)$
4. $I_C = (\beta)(I_B) + (I_{CBO})(\beta + 1)$

Common Base Amplifier

1. $= \frac{I_C}{I_E}$
2. $= \frac{\beta}{\beta + 1}$

Common Collector Amplifier

1. $\gamma = \frac{I_E}{I_B}$
2. $\gamma = \beta + 1$

Bias Stability

1. $S = \dfrac{(R_B + R_E)(\beta + 1)}{R_B + (\beta + 1)\ R_E}$

Decibel

A. $dB = 10\log(10)\ \dfrac{P_2}{P_1}$

B. $dB = 20\log(101)\ \dfrac{E_2}{E_1}\sqrt{\dfrac{Z_1}{Z_2}}$

C. $dB = 20\log(101)\ \dfrac{I_2}{I_1}\sqrt{\dfrac{Z_2}{Z_1}}$

Feedback Amplifiers

A. $A_f = \dfrac{A_v}{1 - \beta A_v}$

B. $e_\varepsilon = e_{in} + \beta e'_{out} = e_{in} + e_f$

C. $e'_{out} = \dfrac{A_v e_{in}}{1 - \beta A_v} = e_{in}A_f = e_\varepsilon A_v$

D. $ed' = \dfrac{ed}{1 - \beta A_v}$

E. $\beta = \dfrac{R_i}{R_f + R_i} \qquad \dfrac{R_E}{R_C}$

Op-Amps

A. $E_{out} = (E_{in_2}\dfrac{R_f}{R_{s_2}}) + (-E_{in_1}\dfrac{R_f}{R_{s_1}})$

B. $E_{out} = e_{in}\dfrac{R_f}{R_s}$

*U. S. GOVERNMENT PRINTING OFFICE: 1985-544-442/16821